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THE EFFECT OF BIOMASS FUEL MOISTURE CONTENT TO THE POWER GENERATION VALUE CHAIN

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ABSTRACT

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The effect of biomass fuel moisture content to the power generation value chain
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With global energy demand increased rapidly, biomass as a sustainable and renewable source can be a substitution of fossil fuel to response to energy crisis and climate change. Finland has positive attitude to increase the use of renewable energy with the target that share renewable energy of energy consumption up to 38% in 2020. Wood fuels to total energy consumption grow to 27% in Finland, of which 40% were forest chips.

The primary aim of the study was to evaluate to what extent moisture content of biomass effect to power generation value chain based on a dynamic model. The analysis includes moisture content prediction model, procurement cost and profitability comparisons between different forest chips biomass supply chain, energy production analysis for heating and electricity generation. Additionally, optimization model of biomass supply chain was also evaluated to minimum supply chain cost with MC constraints.

According to the results of the study, biomass procurement cost and energy production cost varies with different harvest and storage time which affect biomass moisture
content change. Tree volume is the most impact for supply chain cost, following MC, storage period, forward distance, interest rate and transport distance separately. For heat generation, fuel price is the most impact, following operation hour, interest rate and MC. Optimization model reveal that total supply chain cost and harvest volume both sensitive with MC constraints, supply chain cost after optimization had a significant decrease.
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Part I mode code

Part II Data Code

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NOMENCLATURE

Latin alphabet

C  cost  €/m3
E  evaporation  mm
i  interest rate  %
I  investment cost  €
k  cost  €/MWh
L  length  m
m  weight  kg
n  year  a
P  precipitation  mm
P  power  MW
q  net calorific value  MJ/kg
t  temperature  °C
T  time  s
v  speed  km/h
V  volume  m3
w  water content  kg H2O/kg dm
x  month  m

Greek alphabet

ρ  density  kg/m3
η  efficiency  %

Abbreviations

CDCF  Cumulative discounted net cash flow
CT  Chipping cost
DML  dry matter loss
EC  Energy content
ED  energy demand
FO  objective function
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>HC</td>
<td>Harvesting cost</td>
</tr>
<tr>
<td>MC</td>
<td>moisture content</td>
</tr>
<tr>
<td>OT</td>
<td>Other cost</td>
</tr>
<tr>
<td>PV</td>
<td>present value</td>
</tr>
<tr>
<td>TR</td>
<td>Transportation cost</td>
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1. INTRODUCTION

1.1 Background

Global energy demand has increased rapidly with an average rate of 1.2% per year to 2035 (BP, 2019), and coming with global economics and environment issues, according to IEA report, global mean temperature would increase around 2.7 °C by 2100, and around 3.5 °C by 2200 under current pathway (Birol, 2018). Renewable energy is considered as an reliable and efficiency way to reduce GHG emission and achieve the target that limit global temperature rise to ‘well below 2°C’ (UN, 2015). The European Union (EU) has the target that renewable energy proportion up to 20% by 2020 and 32% by 2030. Biomass as a sustainable and renewable source, with a share about 42% of primary renewable production in EU in 2017, can be a substitution of fossil fuel to response to energy crisis and climate change.

![Figure 1.1 World Primary Energy Consumption](BP, 2019)

Finland has positive attitude to increase the use of renewable energy and the use or renewable energy sources growing annually, the target is to share renewable energy of energy consumption up to 38% in 2020 (StatisticsFinland, 2018), reach the target agreed in government program and the EU by 2030, and reduce GHG by 80-95% by 2050. (Työ- ja elinkeinoministeriö, 2017).

The consumption of renewable energy sources in Finland account for 37% in 2018, and wood fuels to total energy consumption grow to 27% which was the most used energy source in Finland (Vertanen, 2019). According to the national report, 20 million m³ of wood fuels used in Finnish for heat and power generation, of which 40% were forest
chips. Including, most of forest chips (7.4 million) used in CHP plant, and only about 0.6 million for small house heating (maa ja metsätalousministeriö, 2019).

Figure 1.2 consumption of Wood fuel in CHP in Finland (maa ja metsätalousministeriö, 2019)

Although the use of forest fuels is benefit to the global environment and help energy independence, However, stakeholders may be not positive if it is not quite a profitable business. Compared to fossil fuel, biomass with lower energy density which need more storage area and higher transport cost, therefore the cost is more sensitive to logistics system (Aalto, 2019). It is necessary to investigate the forest biomass value chain system, from harvesting to energy production, and design the biomass supply chain cost efficiency to decrease the cost to a reasonable level to improve material use for energy purpose.

1.2 Energy wood Supply chain

An energy wood supply chain is a system to delivering biomass from suppliers to end users, and resources of different materials include whole trees, stem wood, stumps and logging residues. These activities involve harvesting, forwarding, storage, chipping (communion), transport, and End user. Figure below represent the supply chains of different material type. Mainly difference for each material is the chipping location in the whole supply chain (Asikainen, 2015).
1.2.1 Harvesting

The first step in the energy wood supply chains is the harvesting trees in the forest. Harvesting means felling trees and transporting them from stand to an intermediate site. Normally harvest method can be divided to two methods: full tree logging and cut to length (CTL) logging (WBA, 2018). whole-tree method means cutting of undelimbed whole trees and transport for the next process, there are no residues left; cut to length method means trees cut to 2-4 meter stem wood, branches and tops removed and left in the stand.

Mechanization vehicles in the wood harvesting improve significantly. Felling technology experienced saw and axe, chain saw, and nearly 99% felling used harvester in Finland now (Strandström, 2018). The trees are cutting by felling head of harvester
which contain a chain saw on it. After felling, trees bunched in piles and left on the strip road and waiting transport to storage site by forwarder. Another Mechanical machine for felling trees were harwarder, which can felling and forwarding trees together. Compared to operating two machines, The advantage of harwarder is save forwarding time and to reduce forward costs (Laitila, 2012).

Figure1.4 Felling Techniques from 1940–2017 (Strandström, 2018)

1.2.2 Forwarding

After harvest, energy wood then transported to roadside. Over the years, the system has become mechanized and it is mainly accomplished by forwarder. Forwarder pick up wood with a loading mechanism and place them in a carrying compartment. By carrying the wood, forwarders can has high carrying capacity per turn, which improves the productivity significantly (Curtin, 1986).

Figure1.5 Forwarding technology, 1940–2017 (Strandström, 2018)

1.2.3 Transport

The aim of transport is to move wood biomass from storage to power plant. Transport material depends whether chipping at roadside or at plant. biomass transport modes
mainly divide into road, railway and waterway transportation. The optimum transporting mode change with demand of fuel and logistical systems. Railway transport is suitable for larger quantities biomass transport and require sufficient railway network, waterway transport also suitable for long distance and no emergency need (WBA, 2018). Meanwhile, compared to road transport, Railway and waterway transport systems need extra loading and unloading site, which increase costs (Karttunen, 2015). For distances below 100 km, trucks are the most cost efficiencies transport mode (Hamelinck, 2004).

![Figure 1.6 Long-distance Transportation Techniques, 1940–2017 (Strandström, 2018)](image)

Wood biomass type, which affect bulk density and energy density, are important role for transportation, energy density range from 0.42 MWh/m³ (unchipped logging residues) to 0.81 MWh/m³ (biomass chipper) for different biomass material (Ranta, 2006). Meanwhile, by increasing transportation load can decrease transport cost, Based on current legislation, 76ton is still the maximum allowed weight for vehicle based on conditions of road, with development of high capacity trucks (HCT) transportation, 100 ton giants truck will be achieved in future (Venäläinen, 2016).

1.2.4 Storage
Biomass Storage is a basic part of wood supply chain, because it ensures energy fuel supply and it improves fuels quality. After harvested at forest, Biomass would be temporary storage before transport. Due to moisture content change, storage time, location are needed to considered when biomass storage in supply chain (Laitila, 2012)
Biomass moisture would change during storage by natural drying. It is the most essential method to reduce moisture content and improve heat value of wood fuel. Weather condition, location and time highly determine the process. Some recommend that biomass dry during summer and use it before winter, in Norway, moisture content after summer natural drying decrease by 12% compared to winter (Filbakk, 2011).

However, a major problem about dry matter loss (DML) appeared with biomass material storage, which can decrease energy density and increase carbon emission. Dry matter losses due to decomposition of biomass material caused by either fungal attacks or spillage of material (Krigstin, 2016), this process will reduce energy value. Dry matter loss varies with different temperature and moisture and oxygen content of the piles, normally it is less than 3 % per a month (Routa, 2015). Mackensen(1999) reported that 7-9% DML for alder and poplar, while lower rate about 2% DML during the first year for spruce and pine. Jirjis(1995) found that higher DML for birch chips storage about 8.7% from May to December.

1.2.5 Chipping
Chipping is used to cut larger pieces of wood to medium sized pieces, is the most important part of wood chips supply chain, woodchips can be used for biomass solid fuels or pulp materials. chipping can increase bulk density of the material twice and transport costs would be lower (Angus-Hankin, 1995). wood can be chipping at roadside or at the terminals. In Finland wood chips from small-sized thinning is73% by roadside chipping and 24% by terminal chipping (Laitila, 2012) Both pros and cons for the two chipping method, transportation costs of roadside chipping would be lower as bulk density increase, Correspondingly, terminal chipping can simplifies the supply chain process, and decrease maintenance costs, and chipping supply would be more efficient (Jäävalli, 2019).

1.3 Biomass supply chain management and optimization
Supply chain is a system involved of many organization, people and activities, to make each independent business group to a coordinated work, Supply chain management includes planning and management of all activities related to procurement, conversion
and all logistics systems, the basic target of supply chain management is to improve supply chain efficiency by sharing information and joint programs (Mentzer, 2001). Numerous variables involved supply chain management, such as harvest type, storage time, location, transportation, etc., which can considered when make a decision. Optimized of the supply chain system is not only just minimum total cost, but should consider economic, environmental and social factors together (Cambero, 2014). Biomass supply chain decision makers also need to understand the complexities involved in biomass resources spatial and temporal distribution and identify many variables, such as the amount of harvest traffic network traffic, recommended inventory levels and resources consumed (Acuna, 2019).

1.3.1 Supply chain decision levels

Supply chain management can be divided into different levels for different purpose and time period, mainly include strategic level, tactical level and operational levels, different levels as shown in figure below.

![Decision making levels](Atashbar, 2018)

1.3.1.1 strategic decisions

Strategic decisions are long term levels, and the focus is on design of biomass supply network, biomass procurement strategies and investment decisions. Based on these studies, decisions can be made on investments in facilities and the forest fuel production
capacity. For biomass based power plant, the availability and harvesting costs of the fuel on the alternative sites for the plant must be assessed when make a decisions about plant location, moreover, form of fuel arrive the plant need confirmed so that arrangement can be made for receiving and storing the materials (Ranta, 2004).

Some research were studied on supply chain about strategic levels. Wang(2012) develop a model for energy crop to determinate optimal locations and facilities. Akgul(2010) develop a model for a bioethanol supply chain to optimal planning with minimum total cost.

1.3.1.2 tactical decisions
Tactical decisions refer to medium term decisions from 1 to 5 years (Acuna, 2019). They are mainly emphasized on logistical systems, to reach objective of the optimization of biomass flows between supplier and end users. To use resource reasonable through the year, decisions should both focus on biomass fuel procurement and demand. for example, harvesting managers should clear raw material volume for fuel production and average cost in each region and periods, meanwhile, power plant demand of forest fuel varies seasonally, the supply and demand of biomass fuel should also change to make a balance (Ranta, 2004). Zhu(2011) describe a multi-commodity network flow model, the goal of the model was to determine warehouse location and harvest size, biomass type and amount harvest and stored in each month.

1.3.1.3 operational decisions
Operational decisions addresses short term goals, include weekly, daily decisions or even hourly. It focus on detailed of operation, daily inventory planning and vehicle planning and scheduling (Acuna, 2019), in order to meet customers’ demand at the lowest cost. This include selection of harvest stands and harvesting methods. Van Dyken(2010) develop an optimization model about operational supply chain planning by consider transport, storage and processing operation.
1.3.2 Optimization techniques

An effective biomass supply chain management can’t leave without efficient optimization techniques. Supply chain optimization can applied at different levels and mainly include supply network design(storage and plant location, etc.), biomass supply chain modeling and decision support systems(DSSs) (Acuna, 2019). Optimization techniques mainly divided into: Mathematical programming; Heuristics methods, Geographic Information Systems (GIS) and Simulation (Atashbar, 2018).

1.3.2.1 Mathematical programming

Mathematical programming is one of widely used methods. It includes the ability to optimize resources under a set of constraints. A mathematical problem mainly includes an objective function and constraints according to different problems, numerous variables and parameters set based on the model. Mathematical models can divide based on the characteristics of variables, objective function and constraints (Atashbar, 2018).

A linear programming model (LP) refers to problems have a linear objective function and linear constraints. Correspondingly, Non-linear programming (NLP) is the model include non-linear objective functions or constraints. Integer programming (IP) model involve all variables are integers. Mixed integer programming (MIP) means models which include both continuous and integers variables (Cambero, 2014).

Many studies have been done on the Mathematical programming research, including, LP and MIP are widely applied methods to solve biomass supply chain problems (Acuna, 2019). Sosa(2015) developed an LP model to manage supply chain with minimum cost on spatial and temporal distribution, and analysis the impact of MC and truck configurations to supply chain cost. Cundiff (1997) developed a model based on linear programming (LP) model for a herbaceous transportation system. Judd (2010) developed an integer programming model to optimization supply chain with minimum transport and storage cost. Mixed Integer linear Programming (MILP) model used by Leduc (2008) to optimize network structure, to the optimal arrangement of plant locations and sizes about wood gasification in Austria. The MILPs can also model biomass supply chain for huge variables. Zhang (2013) developed a model by MILP methods to minimum annual cost for 99 countries and research monthly change over 30 years, 145,000 variables and 219,000 constraints were involved in the model. Bruglieri
(2018) studied biomass supply chain to minimum total cost solved with a mixed-integer non-linear programming (MINLP) model.

1.3.2.2 Heuristics

Heuristics is considered a good solution to solve complex problems when it took too much time by mathematical model. Heuristics faster than mathematical model but lower optimality. Kinds of metaheuristic algorithms have been developed mainly include genetic algorithm (GA), particle swarm optimization (PSO), binary honey bee foraging (BHBF) and simulated annealing(SA). Venema (2003) developed a model based on GA method to optimize plant location and energy demand for biomass network design. PSO was also used by López (2008) to optimal bioenergy facility location and supply in rural area.

1.3.2.3 GIS modelling

GIS is a system to store, capture, manipulate and display geographic data (Atashbar, 2018). Spatial data normally associated with attribute data, for example, name, level and capacity of a building, can help a planner to do spatial analysis. Based on previous research associated with biomass supply chain studies, GIS is a useful tool to logistics optimization, transport routing, and can help to analysis biomass availability with demand in the supply area. Aalto (2019) built an agent-based model (ABM) based on GIS analysis, to optimize biomass logistic arrangement in different locations in EU and evaluate HCT devices use in Finland. By using GIG model, Ranta (2005) developed a logging residues potential supply map in different regions in Finland.

1.3.2.4 Simulation methods

For complex systems with a lot of interactions and uncertainties, it is not convenient to optimize the model, in this case, the simulation method is a tool of choice. Model existing systems with dedicated software and then simulate their long-term activities very quickly to calculate various performance evaluation criteria.

1.3.3 Mathematical programming Solvers

As mentioned above, a lot of mathematical models such as LP, MILP, MIP, etc., and some solvers can be applied to optimize mathematical model. Atashbar (2018) summarized 86 papers about optimization of biomass supply chain in different decision levels, for research based on mathematical programming, in which 33 papers use CPLEX solver and 3 papers solved by LINDO solver. The selection of tools depends on model problems and the experience of the researcher, most importantly, connection to other applications and platform support. Here compared the two popular solvers for mathematical programming.

1.3.3.1 CPLEX solver

IBM CPLEX is the world class and widely used large scale solver for integer, linear and quadratic programming (IBM, 1987), (Optimization Programming Language) OPL is an algebraic model language used to simplify solving optimization problems. Compared to other programming language, coding is shorter and easier to use.

IBM ILOG CPLEX Optimization Studio™ is the software package with CPLEX solver built in. the optimizer software can solve large scale optimization models with millions of constraints and variables, and it can be accessible through other optimization software such as Excel, Matlab, etc. For now, license is free to students and academics, and right and efficient support can get from IBM community when need help.

1.3.3.2 LINDO Solver

LINDO system is also the professional package to solve linear, nonlinear, integer and stochastic programming. They have two products in which LINGOTM provides a
completely integrated package, meanwhile the Excel add-in solver "What's Best!" was able to develop optimization models in a spreadsheet (LINDO, 2019).

Similarly, LINDO system has their own modelling language Lingo, and free license for academic use. Although LINDO solver existed longer than CPLEX solver, there are not much support and guidance online which may limit their application.

1.4 Moisture content measurement
Moisture content is an important parameter of wood fuel, the whole energy production value chain would be benefitable if moisture content can be monitored in advance and accurately, variation of moisture content can also change the supply chain strategy, therefore it is quite useful to develop a fast and convenient methods for moisture measurement.

Conventional moisture measurement is oven-drying method in the laboratory, which collect material in a few hours and took more time on measurement, in order to get a good performance and predication, real time and online moisture measurement is required. Current measurement solutions mostly based on radiation technology have been applied in the biomass value chain.

1.4.1 microwave-based moisture measurement
Microwave methods is based on attenuation, phase shift and resonance sensor (Järvinen, 2013). snow or ice the sample containing cannot be measured. In some field gauges to perform the correct analysis, density and temperature of the material also need to know (Järvinen, 2013).

BMA is a microwave-based biomass moisture developed by Senfit Ltd. In this device, 15 liters Sample had to be feed and grinded in the system to measurement by BMx sensor. Moisture measurement for each grade (stumps, bark, etc.) separately had a good result with standard deviation less than 5% compared to laboratory results and data can be monitored in real time. But for mixed types materials such as logging residues with bark, less accuracy still in this stage and measurement accuracy needed improved.
1.4.2 Nuclear Magnetic Resonance (NMR) method

The NMR spectrum is based on the interface between the external magnetic field and the nuclear magnetic moment. The principle is to measure the resonance signal of hydrogen atoms in the free water molecules (Järvinen, 2013). The device can measure any particle size and material type accurately no more than two minutes, but less accurately when materials contain ferromagnetic metals. Österberg (2016) compared moisture measurement with five biomass material and three moisture levels, results show that difference between the NMR oven drying method was about 1.0 ± 3.8 %. VTT (Järvinen, 2013) compared moisture measurement by MR device with standard method (EN 14774), test show the same precise results with traditional method.

1.4.3 NIR-spectroscopy measurement

Near infrared spectroscopy (NIRS) is an optical technology which use near infrared light 700-2500 nm for measurement (Jäävalli, 2019). Compared to other methods, NIR can measure fast and non-destructive without sample preparation; It can installed on convey belter and monitor online in real time for moving sample, meanwhile energy density and ash content can also be measured and no need for extra parameter(density, etc.) measurement.

However, some disadvantage that still need improvement for this method (Sikanen, 2016): Firstly, it only measure surface of the material and depth above 1mm cannot
detected; Secondly, impurities material such as sand, snow and plastic can affect measurement; Thirdly, results sensitive to temperature change.

1.4.4 X-ray method

In X-ray fluorescence analysis, biofuel measurement based on the wavelength and intensity of the X-rays emitted by the material (Whiston, 1987). Figure below shows scheme of this method. The X-ray device scans the fuel on the conveyor belt, main results such as moisture content, foreign matter and volume can be acquired after image analysis (Sikanen, 2016). Compared to other methods, these measurements are not sensitive to temperature change and impurities (Järvinen, 2013)

![Figure1.9 Fuel X-Ray measurement (Sikanen, 2016)](image)

The Inray Ltd. developed a solid fuel quality Analyzer based on Online x-ray scanning. The system can measure moisture, foreign material and heat value in real time. UPM-Kymmen Plc tested this system compared to sampling-based methods. Results show that The Inray Fuel system can estimate foreign matter content and more accurate than current methods,

Swedish Company Mantex Ab also develop X-ray based method named qDXA–XRF for online biofuel measurement. The system combined two different X-ray technologies, X-ray absorptiometry (qDXA) and X-ray fluorescence (XRF) analysis together and can analysis moisture content, foreign matter, ash content and heating value simultaneously. Compared to other methods estimate heating value through moisture content, qDXA–XRF method estimate carbon/oxygen content/ratio which has more accuracy. Results show that Mantex device can decrease uncertainty and more accurately than oven
method to estimate biofuel heating value, mainly parameters including moisture, ash content and heating value can be acquired in one minute with good results (Torgrip, 2017).

1.5 Current research

Numerous research were studied based on biomass supply chain and energy production process, Ranta (2004) developed a method combined with GIS-analysis and supply chain cost analysis to evaluate logging residues supply chain. Petty (2014) evaluate profitability and supply cost to improve efficiency of energy wood supply chain. LUKE (Sikanen, 2016) developed drying models and measurement technologies, data returned to ERP system for better supply management. Vakkilainen (2017) investigated electricity generation cost of different plants in Finland by using annuity method. However, previous research mostly emphasis on parts of the value chain, still limited research on the overall value chains of forest biomass from harvesting to energy production (Karttunen, 2015). This thesis is try to build a calculation model of whole value chain cost, to find association with each part, and investigate the effect of moisture content change to the whole value chain.

1.6 Objective of the research

The main objective of the study was to evaluate to what extent moisture content of biomass effect to power generation value chain. It is supposed that moisture content of biomass material decreases with natural drying during storage time, supply cost and energy production cost varies correspondingly. In this thesis work, firstly develop a calculation model to evaluate this phenomenon during the whole process. Secondly, since relationship between moisture content with supply cost had been recognized, based on this calculation model, a dynamic model was built and small diameter wood whole tree chips supply chain were selected for case study, optimization of biomass supply chain were also evaluated to minimum supply chain cost with MC constraints.
The specific objectives of the study were as follows:

1) Based on Moisture content prediction model, evaluate harvest month and storage period effect to biomass moisture content and dry matter loss.

2) Supply chain cost model were developed to estimate procurement cost of whole tree chips by different supply chain methods. The model compares different logging system include two machine system and harwarder system, and analysis when trees were roadside chipping or terminal chipping.

3) kemera subsidy system model were developed to calculate maximum financial support can get to a whole stand in Finland.

4) describe cost structure in heat or power production for biomass fuel.

5) based on the models, calculate profitability of forest chips supply chain, and evaluate each parameters effect to the results by sensitive analysis.

6) Calculate Profitability of energy projects and evaluate parameters effect to the results.

7) Based on models above, build an optimization model, to minimum supply chain costs for an tactical decision and evaluate the effect of biomass MC
2. METHODOLOGY

2.1 Moisture model

2.1.1 Moisture prediction model

Moisture content is the most important element which affect biomass property such as heat value and density. Normally energy wood would leave roadside monthly until next process, and moisture content would change during natural drying, the most important parameters about natural drying are evaporation, precipitation, humidity, temperature and other conditions (Routa, 2015). Therefore, moisture prediction models based on weather conditions were needed to evaluate and predict moisture content change of energy wood.

Many studies have developed various models for moisture content prediction since 1980s (Filbakk, et al., 2011; Heiskanen, 2014; Liang, 1996; Routa, 2015; Sikanen, 2012; Stokes, 1987). Raitila (2015) and Aalto (2019) compare models by Heiskanen and Routa in same condition, both models are accurate for energy supply estimation, and Heiskanen’s model more suitable for long-term storage (Aalto, 2019). Therefore, in this study, Heiskanen’s prediction model was used in the further calculation.

In Heiskanen model, moisture can be associated with precipitation and relative humidity which can be easily acquired from local weather statistics. Meanwhile, precipitation,
evaporation and equilibrium water content fitting polynomial also generated based on measurement data from 1991 to 2005 located at Mikkeli. Model can be calculated with the following formulae:

\[ w_{i+1} = w_i + a \cdot \frac{\Sigma p}{w_i - w_{eq} + b} - c \Sigma E \cdot (w_i - w_{eq}) \]  
(2.1)

\[ M_{i+1} = 100 \cdot \frac{w_{i+1}}{w_i + 1} \]  
(2.2)

Precipitation and evaporation formula described as follows:

\[ \Sigma E \,(mm) = 0.0476x^5 - 1.5947x^4 + 17.865x^3 - 73.301x^2 + 126.47x - 70.151 \]  
(2.3)

\[ R^2 = 0.9993 \]

\[ \Sigma P \,(mm) = 0.0202x^5 - 0.7759x^4 + 10.657x^3 - 60.868x^2 + 177.15x - 128.38 \]  
(2.4)

\[ R^2 = 0.9991 \]

Equilibrium water content function with relative humidity described as:

\[ w_{eq} = 0.404 RH^3 - 0.274 RH^2 + 0.1173 RH + 0.062 \]  
(2.5)

\[ R^2 = 0.9993 \]

where

\( w_i \)  Biomass water content, kg\( H_2O \)/kg\( dm \)

\( w_{eq} \)  Equilibrium water content

\( RH \)  relative humidity, %

\( \Sigma E \)  cumulative evaporation, mm

\( \Sigma P \)  cumulative precipitation, mm.

\( x \)  month (1 to 12 equals January to December)

### 2.1.2 Dry matter loss

As mentioned above, moisture content of material change during storage, moreover, dry matter also loss during storage, which caused either by microbial activity, or spillage of material during handling and storage (Routa, 2015). 1% dry matter loss is assumed suitable value for inventory calculation (Sikanen, 2016). To evaluate effect of DML to material volume after storage, the amount of dry matter and moisture content based on energy wood weight were calculated as following:
\[ m_0 = \rho_0 \times V_0 \] (2.6)

\[ m_{MC0} = m_0 \times MC_0 \] (2.7)

\[ m_{DM0} = m_0 \times (1 - MC_0) \] (2.8)

where,

- \( m_0 \): total weight before storage, kg;
- \( MC_0 \): moisture content before storage, %;
- \( \rho_0 \): density before storage, kg/m³;
- \( V_0 \): total volume before storage, m³;
- \( m_{MC0} \): moisture content before storage, kg;
- \( m_{DM0} \): dry matter content before storage, kg.

Dry matter and moisture weight after storage can be calculated using the DML, total weight after storage can also be acquired, formulas as following,

\[ m_{DM1} = m_{DM0} \times (1 - DML) \] (2.9)

\[ m_{MC1} = m_{DM1} \times MC_1 / (1 - MC_1) \] (2.10)

\[ m_1 = m_{DM1} + m_{MC1} \] (2.11)

where,

- \( MC_1 \): moisture content after storage, %;
- \( \rho_1 \): density after storage, kg/m³;
- \( m_{MC1} \): moisture content after storage, kg;
- \( m_{DM1} \): dry matter content after storage, kg;
- \( m_1 \): total weight after storage, kg;
- \( DML \): dry matter loss during storage, %.

Finally, volume after storage can be calculated as,

\[ V_1 = \frac{m_1}{\rho_1} = \frac{\rho_0 V_0 (1 - MC_0) (1 - DML)}{\rho_1 (1 - MC_1)} \approx V_0 (1 - DML) \] (2.12)

### 2.2 Productivity and supply chain cost analysis

The aim of the study was to compare and analyze procurement cost by different supply chain. The compared logging system include harvester-forwarder method(two-machine) and logging by harwarder. Two chipping methods were compared in this study: trees chipped at roadside after storage or whole tree transport and chipping at terminal.
2.2.1 Data analysis of the logging time study

In this work, time studies methods were applied and time consumption of the main work elements in the logging system was formulated by equations based on previous research. Results of time consumption will be transformed into productivity for supply chain cost analysis. Timberjack 810B forwarder and Timberjack 720 harvester were applied in two-machine supply chain time study. Valmet 840 applied for the harwarder time study.

In the two machine study, the main work elements for felling were (Laitila, 2012): 1. Opening strip road, 2. Felling and bunching; the main work elements for forwarding were: 1. Moving, 2. Loading, 3. Forward to landing and back empty to terrain, 4. Unloading. Meanwhile in the harwarder study, work elements for logging were each element above.

Here summarize the time consumption equations for the two logging method, to simplify comparison, unit for each equations unified into second per m³ (s/m³). The equations for time consumption in each work elements by regression analysis method were applied as below.

2.1.1.1 Opening of strip road

Tree volume with branches (dm³) and density of the cutting removal were common variables in the two equations for the time consumption of the strip road opening. In harwarder system model, length of the strip road, which dependent on the size of the load space and load capacity of harwarder were also taken in account.

Time consumption when opening strip road formulate as,

a) for two machine system

\[
T_{strip\ road} = \frac{0.277 + 2412.301/y}{v_s}
\]  \hspace{1cm} (2.13)

\[R^2 = 0.71\]

b) for harwarder system:
\[ T_{\text{strip road}} = \frac{T_{\text{opening road}} \times L}{v_t} \]  
(2.14)

\[ T_{\text{opening road}} = -10.474 + 0.46 \: v_s + 0.007534 \: y \]  
(2.15)

\[ R^2 = 0.58 \]

where

\( T_{\text{strip road}} \) opening strip road time, s/m³

\( T_{\text{opening road}} \) Opening of strip road, s/m

\( y \) Removal density, stems/ha

\( L \) Strip road length, m

\( v_t \) Harwarder load capacity, m³.

\( v_s \) Tree volume with branches, dm³;

2.1.1.2 Felling and bunching

Tree volume and number of trees were the two variables in time consumption during felling and bunching.

Time consumptions were formulated as:

a) for two-machine system:

\[ T_{\text{processing}} = \frac{22.815 + 0.0312 \: v_s - 3.373x}{v_s} \]  
(2.16)

\[ R^2 = 0.64 \]

b) for harwarder system:

\[ T_{\text{processing}} = \frac{17.848 + 0.07304 \: v_s - 1.883x}{v_s} \]  
(2.17)

\[ R^2 = 0.60 \]

where

\( T_{\text{processing}} \) Processing time, s/m³;

\( v_s \) Tree volume, dm³;

\( x \) Trees numbers in each crane cycle;

Including, trees number per crane cycle was formulated as:
\[ x = 4.616 - 0.0467 v_s + 0.0001987y \]  
\[ R^2 = 0.47 \]  

where

- \( x \)  Tree amount per crane cycle;
- \( v_s \)  Tree volume, dm³;
- \( y \)  tree density in the area, trees/ ha

2.1.1.3 Moving

The moving time means driving time between loading positions during loading, since the distance between loading spot is only meters close, the equations only depends on the energy wood density.

Time consumptions of moving time were formulated as:

a) for two machine system

\[ T_{moving} = 4.925 + \frac{233.094}{z} \]  
\[ R^2 = 0.88 \]  

b) for harwarder system:

\[ T_{moving} = \frac{0.3734}{v_s} + \frac{1990.103}{y} \]  
\[ R^2 = 0.90 \]  

where

- \( T_{moving} \)  Moving time during moving, s/ m³;
- \( y \)  tree density in the area, trees/ ha
- \( z \)  energy wood concentration, m³ per 100m strip road
2.1.1.4 Loading at stand

Time consumption of loading time means wood loading work at each loading spot. The most important factor during loading was grapple load volume. The loading time were formulated as,

a) for two machine system

\[
T_{\text{loading}} = -81.419 + \frac{43.906}{v_{\text{grapple}}} \tag{2.21}
\]

\[R^2 = 0.65\]

b) for harwarder system:

\[
T_{\text{loading}} = 36.981 + \frac{22.962}{v_{\text{grapple}}} \tag{2.22}
\]

\[R^2 = 0.88\]

where

\[T_{\text{Loading}} \quad \text{Loading Time, s/m}^3\]

\[v_{\text{Grapple}} \quad \text{Grapple load volume, m}^3\]

The grapple load volume can be formulated as,

a) for two machine system:

\[
v_{\text{grapple}} = 0.0678 + 0.21 \sqrt{v_{\text{C&L stop}}} \tag{2.23}
\]

\[R^2 = 0.62\]

b) for harwarder system:

\[
v_{\text{grapple}} = 0.01935 + 0.524 v_{\text{C&L stop}} \tag{2.24}
\]

\[R^2 = 0.68\]

where

\[v_{\text{Grapple}} \quad \text{Grapple load volume, m}^3\]

\[v_{\text{C&L stop}} \quad \text{Cutting and loading stop size, m}^3\]

The size of cutting and loading stop can be formulated as:

a) for two machine system:
\[ v_{C\&L\ stop} = 0.138 + 0.04107z \quad (2.25) \]
\[ R^2 = 0.74 \]

b) for harwarder system:
\[ v_{C\&L\ stop} = 0.0724 + 0.02095z \quad (2.26) \]
\[ R^2 = 0.55 \]

where
\[ v_{C\&L\ stop} \quad \text{Cutting and loading stop size, m}^3 \]
\[ z \quad \text{Energy wood concentration, m}^3 \text{ per 100 m strip road} \]

2.1.1.5 Forwarding to landing and driving back to the stand empty

According to time study by Laitila, Two machine system and harwarder system have same regression model (Laitila, 2016), time consumption was only associated with forward distance. For driving with load and back empty to the stand, time consumption were shown as below:

1) Driving with load
\[ T_{DrivingL} = \frac{3.99+1.493 l_i}{v_l} \quad (2.27) \]
\[ R^2 = 0.94 \]

where
\[ T_{DrivingL} \quad \text{Forwarding with load time , s/ m}^3 \]
\[ l_i \quad \text{Forwarding distance, m}; \]
\[ v_l \quad \text{load space size, m}^3 \]

2) Driving empty load
\[ T_{empty\ load} = \frac{10.868+1.24 l_e}{v_l} \quad (2.28) \]
\[ R^2 = 0.96 \]

where
\[ T_{empty\ load} \quad \text{Empty driving time, s per m}^3 \]
\[ l_e \quad \text{Forwarding distance, m} \]
Size of load space, m³

2.1.1.6 Unloading

Unloading time only associated with grapple load size. In the time studies the grapple load volume for unloading was 0.3 m³ on average.

\[ T_{unloading} = 15.154 + \frac{16.689}{v_{u-grapple}} \]  \hspace{1cm} (2.29)  
\[ R^2 = 0.28 \]

b)  
\[ T_{unloading} = 14.367 + \frac{12.009}{v_{u-grapple}} \]  \hspace{1cm} (2.30)  
\[ R^2 = 0.71 \]

where

\( T_{unloading} \)  unloading time, s/m³;  
\( v_{u-grapple} \)  grapple load volume, m³

For two machine system, the effective felling time \( T_{felling} \) and forwarding time \( T_{forwarding} \) can be calculated respectively as follows,

\[ T_{felling} = T_{strip road} + T_{processing} \]  \hspace{1cm} (2.31)  
\[ T_{forwarding} = T_{moving} + T_{loading} + T_{driving} + T_{unloading} + T_{empty load} \]  \hspace{1cm} (2.32)  

For harwarder system, The effective logging time consumption \( T_{harwarder} \) was the sum of the main working elements.

\[ T_{harwarder} = T_{felling} + T_{forwarding} \]  \hspace{1cm} (2.33)

2.2.2 Transport Time study

Total transportation time consisted of round drive time and terminal time. Terminal time include biomass loading at storage land, unloading at end user location, auxiliary time, etc., which based on personal skills, varies in different situations (Ranta, 2005). Driving
Time consumption of transport is typically formulated as a function of driving distance and based on the capacity of timber trucks. In time study the trucks were considered as fully loaded drive and empty back. According to previous study of chip truck, driving speed as a function of distance was formulated as:

\[ v_{load} = -0.44591 + 31.695 \times \ln(L) \]  
\[ v_{empty} = 5.7917 + 30.63 \times \ln(L) \]

where,

\( v_{load} \)  
Driving speed with full load, km/h

\( v_{empty} \)  
Driving speed when empty back ,km/h

\( L \)  
Driving distance, km

\[ T_{driving} = \frac{L}{v_{load}} + \frac{L}{v_{empty}} \]  
(2.36)

Loading hour

\[ T_{load} = \frac{V_{load}}{E_c} \]  
(2.37)

where

\( T_{load} \)  
loading hour,h;

\( V_{load} \)  
loading size, m³;

\( E_c \)  
Chipper's productivity per operational hour, loose-m³.

Total load and unload time can be defined as:

\[ T_{load\&unload} = T_{load} + T_{unload} + T_{auxiliary} \]  
(2.38)
2.2.3 Supply chain Procurement cost calculation method

Figure below shows that the production stage of different supply chain, it is defined that supply chain start with organizing, following logging method, roadside storage, chipping, transport and finally received by consumer. The results were given as euro per MWh(€/MWh) and per solid volume(€/m3).

![Diagram of different Supply chain in this work](image)

The storage cost was calculated as the interest of logging, stumpage and organization cost based on the storage time, which as the following equation:

\[
C_{storage} = \frac{m_{storage} \times i \times (C_{organization} + C_{stumpage} + C_{logging})}{12}
\]  

(2.39)

where,

- \(C_{storage}\) storage cost, €/m3;
- \(C_{stumpage}\) stumpage cost, €/m3;
- \(C_{organization}\) organization cost;
Detailed cost of chips production supply chain can be defined as below. The costs (€/m³) for each work element were calculated by dividing the hourly cost by gross effective time productivity (E₁₅). Effective time productivity of different work element were based on time-consumption functions in the previous study, gross effective time productivity which considered the delay time less than 15 min were converted from the effective time (E₀) productivity through coefficient use.

Organization cost was set as 2.5 €/m³ and stumpage prices 4 €/m³ for all supply chains, Hourly cost and the gross effective time based on previous research (Laitila, 2015). Main productivity and parameter for different supply chains were shown in table below.

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organization cost</td>
<td>€/m³</td>
<td>2.5</td>
</tr>
<tr>
<td>The stumpage price</td>
<td>€/m³</td>
<td>4</td>
</tr>
<tr>
<td>Hourly cost of the harvester</td>
<td>€/E₁₅h</td>
<td>102.3</td>
</tr>
<tr>
<td>Gross effective time (E₁₅h) coefficient for harvester</td>
<td>-</td>
<td>1.3</td>
</tr>
<tr>
<td>Hourly cost of the forwarder</td>
<td>€/E₁₅h</td>
<td>81</td>
</tr>
<tr>
<td>Load capacity of forwarder</td>
<td>m³</td>
<td>6.2</td>
</tr>
</tbody>
</table>
Gross effective time (E15h) coefficient for forwarding - 1.2
Gross effective time (E15h) coefficient for harwarder - 1.25
The cost of chipping at the terminal or end use facility €/m³ 5.5
roadside chipping cost €/m³ 8
Loading& unloading cost for transport €/h 47
driving cost for transport €/h 68
unloading time h 0.5
auxiliary time h 0.3

2.2.4 Biomass property parameters

2.2.4.1 Moisture content to Density of material

Densities of different materials were calculated as a function of basic densities of tree species and moisture content. Basic densities for trees species were used according to Hakkila (1978). Meanwhile, forest chips bulk density calculated based on solid wood density only considered volume change, and bulk chip volume (bulk-m³) was considered 2.5 times higher than solid wood volume (m³) (Laitila, 2016).

Table 2.2 Average basic density of different timber species (Hakkila, 1978)

<table>
<thead>
<tr>
<th>Species</th>
<th>Basic density, kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>385</td>
</tr>
<tr>
<td>Spruce</td>
<td>400</td>
</tr>
<tr>
<td>Birch</td>
<td>475</td>
</tr>
</tbody>
</table>

The density for different species were calculated according the following regression model,

\[
\rho_{\text{species}} = (4966.3MC^3 - 2851.8MC^2 + 1090.1MC + 418.79) \times \frac{\rho_{\text{basic}}}{440}
\]  

(2.40)

where

\[
\rho_{\text{species}} \quad \text{solid density, kg/m³.}
\]

\[
\rho_{\text{basic}} \quad \text{basic density when MC=0, kg/m³.}
\]

\[
\text{MC} \quad \text{moisture content, %.}
\]
2.2.4.2 Moisture content to energy content

The relationship between moisture content and energy content can be used with the weight to calculate the energy content of the biomass. Net calorific value of material as received can be calculated based on standard EN 14961-1 (Ari Erkkilä, 2008).

\[ q_{\text{net,ar}} = q_{\text{net,d}} \times \frac{100 - MC}{100} - 0.02443 \times MC \]  

(2.41)

where,

- \( q_{\text{net,ar}} \) net calorific value as received, MJ/kg.
- \( q_{\text{net,d}} \) net calorific value in dry basis, MJ/kg
- MC moisture, %.

Average net calorific value of different timber species according to VTT report (T272) as below.

Table 2.3 Average net calorific value of different timber species on a dry basis (Alakangas, 2016)

<table>
<thead>
<tr>
<th>Species</th>
<th>net calorific value, MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>19.6</td>
</tr>
<tr>
<td>Spruce</td>
<td>19.2</td>
</tr>
<tr>
<td>Birch</td>
<td>19.2</td>
</tr>
</tbody>
</table>

2.3 Kemera subsidy system

In order to encourage production of small sized wood chips in young stand, the Act on the Financing of Sustainable Forestry (KEMERA) issued by Finland’s Ministry of Agriculture and Forestry (MMM) to provides government subsidies for the production of wood chips. The Kemera support is only valid for young forest stands owned by private forest owners in Finland (Petty, 2011), Subsidy for young forest management is 230 € / ha. If small trees are harvested in the context of young forest management, the aid may be increased to EUR 430 € / ha (metsakeskus, 2019).
2.4 Energy production Cost analysis

Annuity method is used for energy product cost calculation in this study, which means annualized investment and operation cost is calculated as equal for the whole lifetime (Tarjanne, 2008). It should be noted that no revenue and tax included in this method.

The cost components of energy product mainly include: capital cost, fuel cost, operation and maintenance cost and heat compensation subtracted only for CHP plant (OECD, 2015), as described formula below. In this work three kinds of energy product were studied for different types of plant: Heat, electricity and combined-heat and power.

\[ k_{\text{total}} = k_c + k_{\text{O&M}} + k_{fu} - k_{\text{heat}} \]  \hspace{2cm} (2.42)

2.4.1. Capital costs

Capital cost is calculated using the annuity factor, which is used to calculate an annual flat rate for the life of the institution, formula described as:

\[ k_c = \frac{C_{n,i} I}{t_h P} \]  \hspace{2cm} (2.43)

\[ C_{n,i} = \frac{i(1+i)^n}{(1+i)^n-1} \]  \hspace{2cm} (2.44)

where,

- \( k_c \) average capital cost, €/MWh
- \( C_{n,i} \) annuity factor, %
- \( I \) investment cost, €
- \( i \) interest rate, %
- \( n \) economical lifetime, a
- \( t_h \) annual full-capacity operating hours, h
- \( P \) maximum power, MW

2.4.2. Fuel costs

Fuel cost associated with fuel price and efficiency, for heat generation, \( \eta_{\text{th}} \) was 1 as no energy condensing loss. Fuel cost can be calculated as follows:

\[ k_{fu} = \frac{k_{fu}}{\eta_b \cdot \eta_{\text{th}}} \]  \hspace{2cm} (2.45)
where,
- $k_{fu}$ average fuel cost, €/MWh
- $h_{fu}$ fuel price, €/MWh
- $\eta_b$ boiler efficiency, %
- $\eta_{th}$ Turbine cycle process efficiency, %

Formula about Boiler efficiency function with fuel moisture content can be given as,
\[
\eta_b = (-0.01MC^2 - 0.019MC + 91.526) - (0.001MC + 0.058) \times \\
(t_{fg} - 120) - \frac{4}{3} \left( \frac{P_{nom}^2}{P} \right)
\] (2.46)

where,
- MC moisture content, %
- $t_{fg}$ flue gas temperature, °C
- $P_{nom}$ boiler size, MW
- $P$ operation power, MW

### 2.4.3. Fixed operating and maintenance costs

Operation and maintenance (O&M) cost means expense for part system operation and maintenance, such as boiler reparation, turbines modification. In this work, annual O&M expense considered as a ratio to total investment cost, O&M cost can be calculated as:
\[
k_{O&M} = \frac{r_{O&M} \times I}{t_h \times P}
\] (2.47)

where,
- $k_{O&M}$ O&M costs, €/MWh
- $r_{O&M}$ Annual O&M ratio, %
- $I$ Investment cost, €
- $t_h$ annual full-capacity operating hours, h
- $P$ maximum power, MW
2.4.4. Heat compensation cost

CHP produces heat and power; and power generation cost is to calculation total costs of generation minus the value of the heat produced. According to joint report by International Energy Agency(IEA) and Nuclear Energy Agency(NEA), heat credit is about USD 44.4/MWh in Europe, (OECD, 2015) which equals to 40 €/MWh. Practically, this has to be done case by case depending different heat price, which is higher in Finland. Heat compensation cost calculated as follows:

\[ k_{th} = \frac{k_{credit} \cdot P_{th}}{P_{el}} \]  \hspace{1cm} (2.48)

where

\( k_{th} \)  Heat compensation cost, €/MWh

\( k_{credit} \)  Heat credit, €/MWh

\( P_{th} \)  Heat generation, MW

\( P_{el} \)  Power generation, MW

The performance and cost data of the biomass power plant investments from literatures presented in table below. Annual efficiency of power plant assumed as 40%, efficiency for heat plant with 0.1 MW function with moisture content presented in this chapter above. O&M cost assumed as percentage of investment cost, economic lifetime as 25 year for all plants, and annual full-capacity operating hours assumed as 5000 h.

Table 2.4 Performance and cost data of power plants

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Unit</th>
<th>0.1 MW</th>
<th>5 MW</th>
<th>30 MW</th>
<th>150 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net efficiency</td>
<td>%</td>
<td>-</td>
<td>-</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Investment</td>
<td>m€</td>
<td>0.04</td>
<td>4</td>
<td>81</td>
<td>310</td>
</tr>
<tr>
<td>Fuel price</td>
<td>€/MWh</td>
<td>20.9</td>
<td>20.9</td>
<td>20.9</td>
<td>20.9</td>
</tr>
<tr>
<td>O&amp;M cost</td>
<td>%</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Economic lifetime</td>
<td>a</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>
Interest rate %  6  6  6  6
full-capacity h/a  5000  5000  5000  5000
operating hours

2.5 Profitability of energy product

This study investigates Profitability of energy product during lifetime.

2.5.1 Cash flow

Cumulative discounted net cash flow (CDCF) method was applied to value the project using time value of money concept. In this method, all future cash flows were evaluated and discounted by capital cost to present value, CDCF can be described as below:

\[ CDCF = -I + \sum_{j=1}^{n} PV_n \]  \hspace{1cm} (2.49)

where,

\begin{align*}
CDCF & \quad \text{Cumulative discounted net cash flow;} \\
I & \quad \text{Investment,} \, \text{€;} \\
i & \quad \text{interest rate,} \, \%; \\
PV_n & \quad \text{present value in year n,} \, \text{€/a;} \\
n & \quad \text{year,a.}
\end{align*}

Present value (PV) method was selected to evaluate financial product with cash flow over time. Present value of cash flow is to describe the future sum of cash flow to a current value, it depends on the net cash flow, time interval and interest rate. Formula described as below,

\[ PV_n = \frac{T_{f,n}}{(1+i)^n} \]  \hspace{1cm} (2.50)

where,

\begin{align*}
PV_n & \quad \text{Present value of cash flow in year n;} \\
T_{f,n} & \quad \text{Net cash flow in year n;} \\
i & \quad \text{interest rate,} \, \%; \\
n & \quad \text{year,a.}
\end{align*}
Net cash flow means differences of revenue and expenditure annually, which reflects return on investment during each year of the review period and determines the Profitability. Net cash flow can be calculated as:

\[ T_f = T_h - (K_{fu} + K_{kk}) \]  

(2.51)

where,

- \( T_f \) net cash flow, €/a;
- \( T_h \) annual revenue, €/a;
- \( K_{fu} \) annual fuel cost, €/a;
- \( K_{kk} \) annual O&M cost, €/a.

Annual revenue as energy production sale can be described as follows:

\[ T_h = P \times t_h \times h_s \]  

(2.52)

where,

- \( P \) operation power, MW;
- \( t_h \) annual full-capacity operating hours, h;
- \( h_s \) production sale price, €/MWh.

Annual fuel cost formula as:

\[ K_{fu} = k_{fu} \times P \times t_h \]  

(2.53)

where,

- \( k_{fu} \) average fuel cost, €/MWh;
- \( P \) operation power, MW;
- \( t_h \) annual full-capacity operating hours, h.

Annual O&M cost described as:

\[ K_{O&M} = k_{O&M} \times P \times t_h \]  

(2.54)
where,

\( k_{\text{O&M}} \) average O&M cost, €/MWh;

\( P \) operation power, MW;

\( t_h \) annual full-capacity operating hours, h.

### 2.5.2 Payback time

Payback time is the period when the revenue takes to cover the cost of investment and began to profitable after that time. In other words, it is the period when Cumulative discounted net cash flow is zero.

The payback time \( (n_p) \) can be calculated as:

\[
CDF = -I + \sum_{j=1}^{n_p} PV_{np} = 0
\]  

(2.55)

### 2.6 Sensitivity analysis

Since there are always some uncertainties about input value, and results can be fluctuated with this change, it is necessary to monitor and evaluate to what extent the input cause uncertainty for the whole systems (Balaman, 2018), therefore, sensitivity analysis is used to evaluate the effect of input value on the results and predict performance of system, to decrease uncertainty and increase reliability of systems.

‘what-if analysis’ tools in Excel was applied in this study to do sensitivity analysis. The tool can explore results for at most two variables without change input value in the table. The outcomes are presented in one form and easy to analysis.

### 2.7 Supply chain optimization model

Optimization model was applied in this study to investigate minimum total cost for supply chain, energy production process was not considered.
2.7.1 Supply chain in model

Two-machine supply chain method as described before was used here for analysis. Whole trees logging by two-machine system, the whole tree were chipped at roadside after storage, and chips were transport to the plant.

2.7.2 Parameters of the model

Unlike other optimization models, simulation was dynamic in this study, main parameter such as biomass density, heat value, harvest, moisture content, forwarding, chipping and transport cost were dynamic and change during different harvest and storage period, the interaction was studied in the chapters before and association was expressed by different matrix which stored in Excel.

As described above, storage cost assumed as interest charge on the logging cost during storage, to simplify the model, storage cost with organization cost and stumpage cost were considered as other cost in the simulation.

2.7.3 Scenarios studied

Based on different moisture content constraints, three scenarios were compared:

Scenario I(SI) the material arriving at the power plant without MC constrained.
Scenario II(SII) MC of biomass arriving at plant constraints between 30% and 45%.
Scenario III(SIII) an even tighter constraint on the MC which meet range between 30% and 40%.

2.7.4 Model Description

The aim of the tactical optimization model was to solve the minimum total cost, determine the optimal wood biomass supply during 2-year planning, Variables considered on a monthly unit, materials were allowed to storage at most 24 months in this case study, and biomass materials must satisfy monthly energy requirement of the plant at the 2nd year.
2.7.5 Mathematical model

The optimization model was described with linear programming, parameters and variables used in the model described as below, table below illustrated that 576 variables and 2316 parameters were considered in this model.

<table>
<thead>
<tr>
<th>Set</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i,j = \text{period} )</td>
<td>( i \in {1\ldots24}, j \in {13\ldots24} ),</td>
</tr>
<tr>
<td>Parameter</td>
<td>Definition</td>
</tr>
<tr>
<td>( EC_{i,j}^{wt} )</td>
<td>Energy content (MJ/kg) for chips harvested in period ( i ) and used in period ( j ).</td>
</tr>
<tr>
<td>( HC_{i}^{wt} )</td>
<td>Harvesting cost (€/m³ solid) for trees harvested in period ( i ).</td>
</tr>
<tr>
<td>( OT_{i}^{wt} )</td>
<td>Other cost (€/m³ solid) for chips, include stumpage cost, organization cost, storage cost, harvested in period ( i ) and used in period ( j ).</td>
</tr>
<tr>
<td>( CH_{i}^{wt} )</td>
<td>Chipping cost (€/m³ solid) for chips harvested in period ( i ) and used in period ( j );</td>
</tr>
<tr>
<td>( TR_{i,j}^{wt} )</td>
<td>Transportation cost (€/m³, loose) for chips harvested in period ( i ) and used in period ( j );</td>
</tr>
<tr>
<td>( MC_{i,j}^{wt} )</td>
<td>Moisture content for chips harvested in period ( i ) and used in period ( j ).</td>
</tr>
<tr>
<td>Variables</td>
<td>Definition</td>
</tr>
<tr>
<td>( X_{i,j} )</td>
<td>Solid volume of whole tree harvested in period ( i ) and used in period ( j )</td>
</tr>
<tr>
<td>( X'_{i,j} )</td>
<td>Loose volume of whole trees harvested in period ( i ) and used in period ( j ).</td>
</tr>
</tbody>
</table>

2.7.5.1 Objective function:

The objective function of the model minimizes total supply chain costs (€) as follows:

\[
FO = \sum_{i,j} X_{i,j} \cdot \left( HC_{i}^{wt} + OT_{i,j}^{wt} + CH_{i,j}^{wt} + TR_{i,j}^{wt} \right) \quad (2.56)
\]

2.7.5.2 Constraints

1) \( ED_i \) is monthly energy demand (GJ) at the power plant, the equation means supply chain meet monthly demand in the 2\(^{nd}\) year, case data from Sosa’s research applied in Ireland region (Sosa, 2015).

\[
\sum_{i,j} X_{i,j} \cdot \left( EC_{i,j}^{wt} \right) > ED_j \quad \forall j \in J \quad (2.57)
\]
Table 2.6 Power plant monthly energy demand (TJ) in 2nd year (Sosa, 2015)

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>130.5</td>
<td>99.4</td>
<td>110.9</td>
<td>139.2</td>
<td>216.3</td>
<td>133.7</td>
<td>142.1</td>
<td>69.1</td>
<td>175.8</td>
<td>101.6</td>
<td>111.4</td>
<td>87.6</td>
</tr>
</tbody>
</table>

2). The equation means weighted average moisture content meet the requirement at plant, and the constraint described as scenarios list above.

\[
\min MC < \frac{\sum_{i,j} X_{i,j}' M_{i,j}^w}{\sum_i X_{i,j}} \leq maxMC \ \forall j \in J
\]  

(2.58)

3) The equation means even volume biomass were harvested in each year, to make sure continuous work and haulage contractors.

\[
\sum_{j \geq i} X_{i,j} = \sum_{j \geq i} X_{i+1,j} \ \forall i \in I
\]  

(2.59)

2.7.6 Implement of the model

The LP model solved by IBM CPLEX, and it contains 576 variable and 2316 parameters, and 1759 results generated for post processing. Most importantly, solver coupled with Excel file included models described above, thus parameters such as moisture content, each supply chain cost was calculated before and stored as matrix in Excel, to make sure the prediction model more reliable. Finally, results return to Excel for postprocessing.
3. RESULTS

Based on methodology described in last chapter, a case study about energy production value chain was built and main results were calculated and analyzed in this chapter. In this case study, wood harvest in January with initial MC 50%, storage time was 10 months until next process, four different supply chain were compared in this study. After received by end users, biomass chips were assumed use directly. The results of the study divided into five parts, moisture content predict model, procurement cost of supply chain, profit of chips product, performance of energy production and supply chain optimization model. Each part was combined, and results were related.

3.1 Moisture prediction model

Figure below represented the monthly precipitation and evaporation calculated as Heiskanen model. Moisture content is then calculated based on monthly precipitation and evaporation according to formulae in chapter 2. There was more evaporation than precipitation during April to September period. It is noted that peak evaporation value appears on July, and during August and September precipitation is higher than other month.

Moisture prediction model for two years of biomass natural drying with different initial moisture content shown in figure below. Figure shows that moisture content decrease for two years natural storage and after two years all biomass moisture content nearly the same, about close to 23.4%, which similar results with Raitila’s research (Raitila, 2015). Moisture content decrease rapidly in Spring from April to July period, during this period...
evaporation rate increase higher than precipitation as shown in figure above, therefore lower air relative humidity during this time (Routa, 2015). Additionally, during summertime, biomass hold moisture content constant, or a little bit increase because evaporation decrease. It should be noted results would be varies for different weather conditions, practically, biomass moisture would be increase during summer time, in some region moisture content even above initial MC after storage (Routa, 2016).

It can be noted that moisture content varies slowly during October to March period, as temperature below freezing and biomass covered with snow during this wintertime, weather condition varies in different storage locations and different years. The model based on data measured during period without snow (Raitila, 2015), therefore average models cannot predict actual changes in wintertime accurately. Routa(2015) suggest that for uncovered storage, moisture content should be increased 5%-unit increase during wintertime.

Based on study above, the model can also predict moisture content and dry matter loss by given harvest month and storage period, which applied as a basic data in the later study. Figure below shows results when initial moisture content assumed as 50%, for example, 120m3 biomass harvest in January and storage for 10 months with initial MC 50% were used for case study in this work, moisture content of material would be 30.2 % as shown in figure below. Meanwhile, DML is 10% for the period as dry matter loss assumed as 1% loss per month, biomass volume can finally be calculated as 108 m³ after storage.
3.2 Supply chain cost and productivity analysis

Procurement cost by different supply chain were analyzed in this section, productivities for each part of supply chain calculated based on time study from literatures review. Based on the last chapter, MC after 10 months storage decrease to 30.2% with 108 m$^3$ volume, which were used for further calculation.

3.2.1. Productivity of logging whole trees

Figure below shows time consumption by the main work elements for two machine and harwarder logging method in a same stand with forward distance was 200m, load size 6.2m, accumulation of whole tress were 60 m$^3$/ha, volume of whole tree were 40 dm$^3$. Two machine system has higher logging efficiency, save 181.6s per volume than harwarder method (925.4s). Including, opening strip road, harwarder took 145.1s/m$^3$ higher than two machine, which was the main difference for the two logging system, since harwarder has to operate crane over the bunk and the small extent of machine to open strip road (Laitila, 2008). In addition, time consumption of harwarder took 174.39 s/m$^3$ for loading work while for forwarder was 115 s/m$^3$. loading work mainly affect by grapple load which means capacity of grapple and affect how many times have to use when loading the same volume wood. Through time study, less grapple load for harwarder(0.167 m$^3$) took more time on loading work, compared to grapple load 0.223 m$^3$ for two machine system,

Time consumption of driving with or empty load were similar for the two logging system as no much difference of drive speed between harwarder and forwarder (Laitila,
Figure also indicate that felling and bunching was main time consumption element which account for 45% of effective working time in harwarder system while 59.4% in two machine system.

![Relative Time consumption of logging system](image)

![Time consumption by working element](image)

**Figure 3.4** time consumption of logging system by different working elements

Figures below illustrate sensitivity analysis about each productivity of whole trees in gross working time (E15h) function with whole tree volume and forward distance based on the two logging system, harvest and forwarding productivity in two machine system were separated for procurement cost calculation, and hour productivity coefficients were 1.3, 1.2 and 1.25 for harvest, forwarding and logging system separately. For two machine system, Harvest productivity increased by 3.8 m3 per gross hour when tree volume increase from 10 to 50 dm3 and forward distance was 200m, and keep constant with forward distance increase, which was 5.9 m3 per gross hour when tree volume 40dm3. Similarly, forward productivity in two machine system keep unchanged with
tree volume increase and decrease by 6.5 m³ when forward distance from 50m to 450m. For harwarder system, logging productivity both concerned with tree volume and forward distance as no separation of harvest and forward process during logging process, therefore logging productivity is lower than harvest and forward in two machine system, which grew by 1.4 m³ when tree volume increase from 10 to 50 dm³, and decrease only 0.51m³ when forward distance from 50m to 450m.

Based on productivity analysis above, logging productivity of harvest system was 5.92 m³/E₁₅h, forwarding system 10.88 m³/E₁₅h and harwarder system was 3.11 m³/E₁₅h, when forward distance 200m, accumulation of whole tress was 60 m³/ha, volume of whole tree was 40 dm³.

![Figure 3.5 productivity as a function of tree volume by different system when forward distance 200m](image)

![Figure 3.6 productivity as a function of forward distance by different system when tree volume 40dm³](image)
3.2.2 Productivity of Transport

Figure below illustrates effective working time consumption for whole tree and chips transport when transport distance 40 km. Time consumption of chips transport took 3.57 h, compared to 3.32h for whole tree transport. Driving time were the same with same drive distance. Meanwhile, as bulk density of chips is much lower than whole trees, so chips transport took 0.25h more loading time than whole tree transport.

![Time consumption of chips and whole tree transport](image)

Sensitivity analysis about time consumption function with transport distance for whole tree and chips as shown in figure below. There was no change about auxiliary and loading time with transport distance change. Drive time decided by drive distance and driving speed, while driving speed only associated with transport distance based on time study.
Figure shows that chips transport took 0.25h more time than whole tree transport on average. when transport distance from 10 km to 150km, time increase from 2.6h to 6.3h for chips transport, while from 2.7h to 4.9 h needed for whole tree transport.

![Figure 3.8 Time consumption as a function of transport distance](image)

**3.2.3 The procurement costs of whole-tree chips**

Figure below shows the procurement cost of whole-tree chips by different supply chain in this case study. The supply chain based on two machine and roadside storage was the cheapest(23.79 €/MWh), while harwareder with plant chipping was most expensive (28.31 €/MWh).Figure indicate that harwarder system was more expensive than two machine system, and supply chain based on roadside chipping was cheaper than terminal chipping.

Within cost structure of whole tree chips supply chain, felling &bunching was significantly expensive which account for about 40%, 9.3 €/MWh. Figure also show that other cost including storage cost were similar, logging(harvest+forwarding)) cost was 13.4  €/MWh for two machine system, and 17.37 €/MWh for harwarder system. Chipping at terminal was 2.9 €/MWh much cheaper than chipping at roadside (4.1 €/MWh). Correspondingly, when transport distance 40km in this study, transport cost based on terminal chipping was more expensive than roadside chipping, which were 3.5 and 1.7 €/MWh respectively.
3.2.4 Sensitivity analysis of supply chain cost

3.2.4.1 The impact of moisture content

Figure below present the procurement costs of different supply chain as a function with moisture content of fresh material, when harvest month in January and storage until November (storage 10 month). Procurement cost per MWh grew with more moisture content of fresh material increase and procurement cost per solid m³ no influenced with MC change. Procurement cost grew by 3.97 €/MWh for harwarder system, while 3.36 €/MWh grew for two machine system when moisture content increase from 10% to 75%. Figure also indicate that procurement cost grew more rapidly when moisture content above 65%, as procurement cost per volume was no relevant with moisture content, the only concerned was energy content per volume, which concerned by biomass density and heat value.
biomass density and net caloric value on dry basis as a function with moisture content presented in figure below.

With MC increase, biomass density grew while heat value decrease. Heat value linear correlation with MC while density function with MC by polynomial regression. For three wood species, Birch with highest density, following spruce and pine, for example when moisture content was 80%, density was 2168 kg/m3, 1825 kg/m3, 1757 kg/m3 for
birch, spruce and pine separately. Finally, the multiplication of density with heat value affect procument cost per MWh change in figure above.

![Figure 3.12: Density and heat value of different wood species as a function of moisture content](image)

3.2.4.2 The impact of transport distance

The procument cost of supply chains were illustrated as a function of transport distance presented in figure below. Figure below indicate that the growth speed for plant chipping is higher than roadside chipping. For harwarder system, The procument cost of plant chipping 0.5 €/MWh lower than chipping roadside when transport distance was 10 km; when transport distance increase to 30 km, same procument cost of the two supply chain which was about 28 €/MWh; After that plant chipping cost higher than roadside chipping and the difference the two supply chain grew to 2.1€/MWh when transport distance was 150 km. Similarly, for two machine system, same procument cost of the two supply chain about 23.5 €/MWh when transport distance 20 km, while cost difference of plant chipping and roadside chipping grew to 2.3 €/MWh when the transport distance was 150 km.
3.2.4.3 The impact of tree volume

Figure below present the procurement cost of supply chains as a function of tree volume. Figure below indicate that supply chain cost decrease with tree volume increase. For harwarder system, the two chipping system nearly the same, decrease from 29.9 to 27.9 €/MWh when tree volume increase from 28dm³ to 52dm³. For two machine system, plant chipping was 0.6 €/MWh higher than plant chipping on average with tree volume change, and 25.2 to 22.8 €/MWh for roadside chipping when tree volume increase from 28dm³ to 52dm³.
3.2.4.4 The impact of forward distance

Supply chain cost as a function of forward distance shown in figure below, Supply chain cost improve with forward distance increase, For harwarder system, plant chipping was 0.25 €/MWh higher than plant chipping on average, grew from 27.8 to 28.8 €/MWh for plant chipping when forward distance from 140 to 260m. For two machine system, plant chipping was 0.6 €/MWh higher than plant chipping on average, grew from 23.4 to 24.2 €/MWh for roadside chipping when forward distance from 140 to 260m.

![Figure3.15 Procument cost as a function of forward distance](image)

3.2.4.5 The impact of interest rate

Supply chain cost as a function of interest rate shown in figure below, Supply chain cost improve with interest rate increase, For harwarder system, plant chipping was 0.25 €/MWh higher than plant chipping on average, grew from 28 to 28.5 €/MWh for plant chipping when interest rate increase from 4.8% to 7.2%. For two machine system, plant chipping was 0.6 €/MWh higher than plant chipping on average, grew from 23.6 to 24 €/MWh for roadside chipping when forward distance from interest rate increase from 4.8% to 7.2%.
3.2.4.6 The impact of storage period

Figure below shows Supply chain cost as a function of storage period when harvest in January. Supply chain cost improve with storage period increase. For harwarder system, plant chipping was 0.25 €/MWh higher than plant chipping on average, grew from 25.1 to 29 €/MWh for plant chipping when storage period increase from 0 to 12 month. For two machine system, plant chipping was 0.6 €/MWh higher than plant chipping on average, grew from 20.8 to 24.5 €/MWh for roadside chipping when storage period increase from 0 to 12 month.
3.2.4.7 Tornado graphs analysis for supply chain cost

Tornado graphs are generated below to compare the change by each parameter mentioned above ± 20% level to supply chain cost. When MC 50%, transport distance 40km, tree volume 40dm³, forward distance 200m, interest rate 6% and storage period 10 month as base case for evaluation. Supply chain cost grew with storage period, interest rate, forward distance, transport distance and MC increase, except tree volume with negative effect as shown in figure. Figures also show that, similar trend in the four supply chain, tree volume is the most impact for supply chain cost, taken harwarder & roadside chipping for example, for each parameter with 20% change, -1.2~3.0% supply chain cost change by tree volume, following MC(2.4%-2.9%) , storage period(-2.5%~2.6%) , forward distance(±1.2%) and interest rate(± 0.8%) respectively, transport distance (±0.5%) had the least impact for supply chain cost. It should also be noted that effect would be different with base case data change, therefore sensitivity analysis results would be different for each study.

![Tornado graphs for supply chain cost analysis](image-url-here)
3.3 Profitability of Supply chain

Profitability with maximum Kemera subsidies for different supply chain shown in figure below, when young stand 3ha, whole trees volume 40dm3, Accumulation of whole-trees 60 m3/ha and transport distance 40km. The study based on same stand, all supply chain system with same income including 7255.7 € energy product sale and 1290 € Kemera subsidy. The figure shows that whole-tree chips from early thinnings cannot be profitable without the Kemera subsidies. The result also indicates that harwarder system cannot be profitable even with Kemera subsidies in this study.

The profitability of whole stand for different supply chains as a function of moisture content when stand area 3 ha, cumulation of whole tree 60m3/ha illustrated in figure below. Similarly, for same stand, Kemera subsidies still not vary over moisture content
change. Less profitability of whole stand when moisture content increase. For two machine system, profitability of roadside chipping was 605 € when MC is 30% which was the most profitable, following plant chipping 439 €, the two chipping system still profitable when MC up to 55%. Correspondingly, for harwarder system none profitable in this situation, and deficit up to -1719 € for roadside chipping with -1800 € for plant chipping responsibly when MC is 75%.

![Figure3.20 Profitability of different Supply chain as a function with MC](image)

### 3.4 Performance of energy production

Chips were assumed use directly for energy generation when arrive at plant, and two machine roadside chipping supply chain system were selected for case study in this section. Based on previous study, chips with MC 30.2% and lower caloric value 12.7 MJ/kg when arrived, chips price was 21 €/MWh according to PIX Forest Biomass Index recently, two different heating plant and two different electricity generation plant for case study, annual full-capacity operating hours were assumed as 5000h, interest rate 6% with lifetime 25h for calculation.

#### 3.4.1 Energy production cost

Cost of electricity and heat product generated by biomass with different capacity presented in figure below. Heat product cost is much lower than electricity product, unlike conventional condensing power plant, there is no energy loss lead by condenser for heating plant. Figure indicate that power cost decrease from 104.03 €/MWh to 90.66
€/MWh when power capacity increase from 30 MW to 150 MW, while 34.99 to 40.16 €/MWh for heat production when power capacity increase from 0.1 MW to 5 MW. Figure below illustrate that fuel cost is the most cost structure, Take 150MW unit for example, the most expensive structure of electricity is fuel cost with 47.99 €/MWh(52.9%), following capital cost only account for 32.33 €/MWh(35.6%) during 25 years lifetime, and O&M cost 10.33 €/MWh(11.4%).

It should be noticed that less competitiveness of biomass compared to fossil fuel and peat without emission trading, according to Vakkilainen’s research (Vakkilainen, 2017), electricity by biomass would be nearly the same with coal(CCS) and peat when CO2 emission price 15 €/t, figure below shows comparation of electricity generation cost with emission trading by different fuel type.
As electricity production cost is much higher than other fuels, therefore biomass as fuel only used in heating plant and CHP plants in Finland (Tarjanne, 2008). Vainio(2011) compare electricity generation cost with heat compensation in four CHP as presented in figure below, and electricity production cost for CHP plant by heat compensation method described in chapter before, unfortunately original parameters missing by author and only comparison results found in the article. Figure below illustrate that, Plant B has the lowest CHP generation cost of -26.9 € / MWh due to heat compensation. Plant D had highest electricity cost of 79.3€/MWh in the four plant before, after heat compensation, generating cost only 4.5€/MWh. For other power plants, production costs range between 35 and 38.6 € / MWh.
3.4.2 Sensitivity analysis of Energy production cost

3.4.2.1 The impact of moisture content

Energy production cost as a function of MC shown in figure below, Energy production cost with moisture content 50% as base case. Energy product cost improve with MC increase, the heat product for 0.1 MW unit grew by 1.64% to 36.3 €/MWh when MC increase 20%, while -1.37% decrease to 35.3 € MWh when MC decrease 20%. Meanwhile less impact of MC to electricity generation plant, taken 30MW unit for example, power generation cost grew -0.88% to 1.05% when MC vary from -20% to 20%.

![Figure 3.24 Energy product as a function of MC](image)

As mentioned above, biomass fuel paid based on energy content basis, when produce certain amount of energy production, although more biomass needed due to lower net calorific value per kilogram, plant owner only has to pay extra cost due to boiler efficiency decrease which affect by MC change. Boiler efficiency as a function of MC as shown in figure below.
3.4.2.2 The impact of full capacity operating hours

Annual cost per kW as a function of full capacity operating hours illustrated in figure below. Annual cost per direct proportion to full capacity operating hours. Highest cost for 30MW unit, which grew from 328.3 €/kW\textsubscript{a} to 705.6 €/kW\textsubscript{a} while lowest cost for 0.1 MW unit, which grew from 70.3 €/kW\textsubscript{a} to 294.7 €/kW\textsubscript{a} when full capacity operating hours increase from 1000h to 8600h.

However, different performance of energy product cost per MWh with operation hour change as shown in figure below. Energy product cost decreases rapidly, for example, 30MW unit with highest cost decrease from 328.4 €/MWh to 119.3 €/MWh when operation hour from 1000h to 4000h, after that cost decrease smoothly to 82.04
€/MWh with operation hour up to 8600h. Meanwhile, 0.1MW unit with lowest price, energy product cost range from 70.3 €/MWh to 32.2 €/MWh when operation hour increase from 1000h to 8600h.

![Figure 3.27 Energy product cost per MWh as a function of full capacity operating hours](image)

3.4.2.3 The impact of fuel price

Fuel price is fluctuated monthly in Finland according to PIX Forest Biomass Index, evaluation of fuel price to energy production cost was more necessary. Energy production cost as a function of fuel price shown in figure below, Energy production cost with fuel price 21 €/MWh as base case. Energy product cost grew with fuel price increase, the heat product for 0.1 MW unit grew by 16.5% % to 41.2 €/MWh when fuel price increase 20%, while -16.5% down to 30.4 € MWh when fuel price decrease 20%. Meanwhile less impact of fuel price to electricity generation plant, taken 30MW unit for example, power generation cost grew -11.4 % to 11.4 % when fuel price vary from -20% to 20%.
3.4.2.4 The impact of interest rate

Figure below investigate interest rate effect to Energy production cost, Energy production cost with interest rate 6% as base case. Energy product cost grew with interest rate increase, the heat product for 0.1 MW unit grew by 1.5% to 36.6 €/MWh when interest rate increases 20%, while -1.5% down to 33.7 € MWh when interest rate decreases 20%. Unlike other input value, more impact of interest rate to electricity generation plant, taken 30MW unit for example, power generation cost grew -3.5% to 3.7% when interest rate vary from -20% to 20%.

3.4.2.5 Tornado graphs analysis for energy production cost

Tornado graphs are generated below to compare the change by each parameter mentioned above ± 20% level to energy product cost. when MC 50%, full capacity operating hours 5000 h, fuel price 21 €/MWh, interest rate 6% as base case for energy product cost evaluation. Energy production cost grew with interest rate, fuel price and MC increase expect operation hours with negative effect as described above. Figures also show that, fuel price is the most impact for heat production cost, taken 0.1MW unit for example, for each parameter with 20% change, 15% heat production cost change by fuel price, following operation hour(4.2%-6.2%) and interest rate(2.2%) respectively,
moisture content (1.3%) had the least impact for production cost. Moreover, a little bit different for electricity production, operating hours has most significant factor to production cost, taken 30MW power plant for example, for each parameter with 20% change, 9%-13% electricity cost change for operation hour, following fuel price (9.2%), interest rate (4.6%), moisture content (0.7%) also had the least impact for production cost.

![30 Tornado Chart for different energy production cost](image)

3.4.3 Profitability of Energy product

As described above, electricity generation also combined with heat product for biomass fuel. To simplify calculation, in this study 5MWth heating plant was taken for example to evaluate profitability of Energy product, investment was 4M€, interest rate 6% and heat product sale price was 70€/MWh. Cumulative discounted net cash flow shown as below. Cumulative discounted net cash flow grew by 10.29 M€ in 15 years, and
repayment time with interest was 4.41 years in this case, therefore project was profitable after 4.41 year.

![Figure3.31 Cumulative discounted net cash flow in 15 years](image)

Repayment time and net present value for 15 years as a function of MC shown in figure below, repayment time grew from 4.38 years to 4.62 years, while net present value for 15 year decrease by 0.45 M€ when MC at plant increase from 20% to 70%.

![Figure3.32 Repayment time as a function of MC](image)

3.5 Optimization model analysis

Tactical decisions development of supply chain management based on mathematical model were studied in the following research. A dynamical simulation model for minimum logistical system cost solved by IBM CPLEX Optimization Studio 12.9.0 studied in this chapter, calculation data for solver read from Excel which were calculated based on results before and write main results to Excel for post processing. Main results generated include total supply chain cost during 2 year period, which also the objective function in this model; harvest volume each month during 2 year period, which was variables in the model; weighted average moisture content received by plant each month, which can be calculated based on biomass MC during each period and
harvest volume during each period; Average supply chain cost per MWh can also calculated based on the results before.

3.5.1 Variation of Moisture content

Monthly average moisture content of biomass when arrive at plant at second year describe in figure below. Scenario I with no MC constraint presented highest MC variation with minimum of 35.6% in September and maximum 49.8% in February and March. In Scenario II (MC 30-45%) MC keep upper limit value 45% in the first six months and variate from June, minimum value 38.5% appear in September. There is no variation in Scenario III when MC constrained to 35-40%, as MC always keep upper limit 40% in all year. Figure also indicate that minimum MC when material arrive to plant in all scenario appear during September. Results from model also indicate that average MC during the two years at plant is 44.2%, 43.5%, 40% for the three scenarios respectively.

![Figure 3.33 MC change under different scenarios](image)

3.5.2 Effect of MC range on supply chain management

To manage supply chain with minimum cost for biomass supplier, volume harvested and storage for two years period can also be solved in this model. Figure below shows fresh biomass harvest volume (z-axis) during each harvest (x-axis) and usage (y-axis) month for scenario I. Based on the third constraints about harvesting and haulage contractors, 8156 m3 wood were harvest each month in scenario I. For example, 1750 m3 biomass harvested in February were stored for 16 months until June in the second
year (18 month as shown in y-axis), others biomass stored for 17 months and use in July the second year (19 month).

![Figure 3.34 biomass harvest volume during each harvest and usage month for scenario I.](image)

To compare the results, harvest volume for each storage time were also evaluated in the following study as shown in figure below. In Scenario I, storage time range from 0 to 18 months, with highest volume being stored for 0 month (37.8%), following stored for 17 months (18%), , In Scenario II, storage time range from 0 to 20 months, with highest volume being stored for 0 month (32%), following 14.7% for 2 months; In Scenario III, longer storage period with tighter MC constraint, highest volume being stored for 12 month (24.6%), following 18.6% stored for 0 month; Average storage month were 5.81, 5.85 and 6.69 respectively for three scenarios, these results also indicate that harvest volume distribution was much sensitive to MC constraints. with more critical in the upper limit of the MC, SIII result in longer storage month to satisfy MC constraint.

![Figure 3.35 volume of biomass storage planning during 24 month period](image)
3.5.3 Effect of MC on supply chain cost

Average supply chain cost of all scenarios presented in figure below, results given both by € per m³ and € per MWh. There was no major difference of three scenarios on solid m³ basis, supply chain cost on SI (51.04 €/m³) and SII (51.01 €/m³) nearly the same, SIII with 51.61 €/m³, only 1.1% higher than SI, as supply chain cost calculated as total cost divided by total volume on solid m³ basis, total volume has similar increase curve as total cost shown in figure below, which making supply chain cost no major difference on MWh basis. Meanwhile, on a per MWh basis, SI (22.37 €/MWh) and SII (22.44 €/MWh) still have similar supply chain cost value, while SIII increase to 23.07 €/MWh, 3.13% higher than SI, as supply chain cost only function with total cost due to same energy demand on three scenarios. Results reveal that total supply chain cost sensitive to MC constraints, which increase from 9.4 M to 9.7 M € when MC from unconstraint to a tight 35-40%.

It should also be noted that procurement cost for two machine and roadside chipping supply chains was 24.77 €/MWh in case study before, average supply chain cost after optimization had a significant decrease by 1.7 €/MWh even with the tightest MC constraint. the results reveal that optimization model is an importance factor for the assessment of fuel quality and optimal planning to minimum supply chain costs.

![Figure3.36 Supply chain cost per solid m³](image-url)
3.6 Evaluation of whole energy generation value chain

Through the study of whole value chain, cumulative cost of biomass material energy generation whole value chain from organization to heat production sale were summarized in figure below. In this case study, two machine& roadside supply chain selected, 5MW heating plant evaluated, wood harvest in January with initial MC 50%, storage time was 10 months, chips price was 21 €/MWh, annual full-capacity operating hours 5000h, interest rate 6% with lifetime 25a for calculation. Left side of the figure was supply chain cost which based on two machine &roadside chipping method, meanwhile right side of the figure was energy production process. It should be noted that different definition of the unit for each process, the value in supply chain process was euros per MWh based on fuel heat value, cost in energy production was euros per MWh based on production energy. The arrow between the total cost and sale price was
profit for each process, figure below shows that final cost was 20.07 €/MWh and 0.93 €/MWh profit of supply chain process, additionally, heat production cost 40.16 €/MWh and 29.84 €/MWh profit for energy production process.

![Figure3.39 Performance of the biomass whole value chain](image)

Meanwhile, Moisture content effect to the whole energy generation value chain were represented in a UserForm generated by Excel VBA, mainly input data include MC prediction model input, supply chain data input and energy production input, results can be illustrated directly by input data change, and linked to results analysis in Excel. Detailed interface as shown in Appendix II.
4. DISCUSSION AND CONCLUSION

Biomass supply chains are complex and affect by numerous factors on the energy material supply chain. Effect of moisture content of biomass to the whole power generation value chain were evaluated in this chapter. The dynamic model which include four modules were built by Excel. The modules not isolated but interaction with other factors.

4.1 Moisture prediction model

Monthly moisture content prediction model for biomass natural drying by Heiskanen were analyzed. moisture content is the most important parameter for biomass supply chain and were affect by temporal and spatial factors. In Heiskanen’s model, moisture content were associated with precipitation, evaporation and equilibrium water content, which would be acquired by local weather statistics. To simplify the calculations, in this study, those parameters would be evaluated by using fitting equations.

Based on this model, moisture content decrease during two years natural storage and finally from initial 50% decrease close to 23.4%. Within one year, moisture content decreases rapidly during spring and summer, and decrease slowly or even increase during autumn and winter season. Based on the model, a matrix was also built in Excel to predict MC by different harvest and storage month, the matrix can be called for further applications.

4.2 Supply chain cost and Profitability of supply chain

The procurement cost of whole tree chips by different supply chains based on time study were calculated in this study. procurement cost varies from 23.79 to 28.31 €/MWh, in which machine and roadside storage supply chain were the most cost efficient while harwarder and plant chipping supply chain were most expensive in the four supply chain under analyzed, within structure of procurement cost, felling& bunching was most significant factor, which account for nearly 40%.

Sensitivity analysis of supply chain cost generated by Tornado graph to compare the effect by each parameter. when MC 50%, transport distance 40km, tree volume 40dm3, forward distance 200m, interest rate 6% and storage period 10 month as base case for
evaluation, result reveal that tree volume is the most impact for supply chain cost, following MC, storage period, forward distance, interest rate and transport distance separately.

Profitability with maximum Kemera subsidies for different supply chain were also studied, young stand 3ha, whole trees volume 40dm3, Accumulation of whole-trees 60 m3/ha and transport distance 40km were selected for case study. Total income 8545.7 € including 7255.7 € energy product sale and 1290 € Kemera subsidy for the same stand. Harwarder system cannot be profitable even with Kemera subsidies in this study, meanwhile two machine system with 655.15€ was the most profitable in the four system.

### 4.3 Performance of energy production

Heat product cost is much lower than electricity product, Power cost from 104.03 €/MWh to 90.66 €/MWh, while 34.99 to 40.16 €/MWh for heat production. Take 150MWel unite for example, the most expensive structure of electricity is fuel cost about 52.9%, following capital cost 35.6 % and O&M cost 11.4 % separately.

Biomass as fuel only used in heating plant and CHP plants as electricity production cost is much higher than other fuels. Electricity production cost for CHP plant by heat compensation method were analyzed for CHP plant. In case study, one plant had highest electricity cost of 79.3€/MWh before, after heat compensation which considered heat production, cost of electricity generation decreases to 4.5€/MWh.

Sensitivity analysis of energy production cost generated by Tornado graph to compare the effect by each parameter. MC 50%, full capacity operating hours 5000 h, fuel price 21 €/MWh, interest rate 6% as base case for energy product cost evaluation. For heat production fuel price is the most impact, 15% heat production cost change by fuel price with 20% level change, following operation hour (4.2%-6.2%), interest rate(2.2%) and moisture content(1.3%) respectively; for electricity production, 9%-13% electricity cost change for operation hour which was most significant to electricity cost, following fuel price(9.2%), interest rate(4.6%), moisture content(0.7%) separately.

Profitability of a heating plant were evaluated by Cumulative discounted net cash flow method, Study reveal that repayment time with interest was 4.41 years in this case, and cumulative discounted net cash flow grew by 10.29 M€ in 15 years. repayment time
The length grew from 4.38 years to 4.62 years, while net present value for 15-year decrease by 0.47 M€ when MC at plant increase from 20% to 70%.

4.4 Optimization model analysis

Biomass supply chains are complex and affect by numerous factors on the energy material supply chain. These factors should be considered to make Supply chain management and optimization. Thus, the use of optimization models is significant to make supply chain cost effective associated these factors.

A dynamical simulation model for minimum logistical system cost solved by IBM CPLEX studied in this study. The aim of the LP model was to minimum total cost with temporal planning, which include harvest volume per month and volume for different storage time during 2-year Constraints of the model set as: 1) meet monthly energy demand at the plant during the 2nd year; 2) meet requirement of moisture content under different scenarios. 3) even volume harvest to make sure continuous work and haulage contractors. Calculation data for solver read from Excel which were calculated based on results before and write main results to Excel for post processing.

Results reveal that supply chain with a higher MC variation when unconstraint MC, meanwhile, the average MC during the two years at plant is 44.2%, 43.5%, 40% for the three scenarios respectively.

Result in this study also reveal that total supply chain cost and harvest volume distribution both sensitive with MC constraints. Average storage month increase from 5.81 to 6.69, supply chain cost increase from 22.37 to 23.07 €/MWh which means total supply chain cost increase from 9.4 M to 9.7 M € for the three scenarios when MC from unconstraint to a tight 35-40%.

Compared to same supply chain cost 25.2 €/MWh in case study before, average supply chain cost after optimization had a significant decrease by 2.13 €/MWh even with the tightest MC constraint. the results reveal that optimization model is an importance factor for the assessment of fuel quality and optimal planning to minimum supply chain costs.
4.5 Evaluation of whole energy generation value chain

In this case study, two machine& roadside supply chain selected, 5MW heating plant evaluated, wood harvest in January with initial MC 50%, storage time was 10 months, chips price was 21 €/MWh, annual full-capacity operating hours 5000h, interest rate 6% with lifetime 25h for calculation. Results reveal that biomass MC was 30.2% after storage, procurement cost for supply chain was 23.8 €/MWh, when subsidy system included, final cost was 20.07 €/MWh and 0.93 €/MWh profit of supply chain process, total profit of supply chain for energy supplier was 288.34 € for the stand. Correspondingly, heat production cost 40.16 €/MWh and profit were 29.84 €/MWh for energy production process.
5. LIMITATION AND SUGGESTION FOR FURTHER RESEARCH

This thesis studied the effect of biomass moisture content to the whole power generation value chain, unfortunately due to limited time the work was limited and need improvement in some sections.

1) Moisture prediction model. Heikkinen’s MC prediction model was used in this study, main parameters were generated by regression equation which data measured in Mikkeli in Finland. To verify the prediction model in spatial and temporal solution, in further research, precipitation and relative humidity data in different region and different period should be collected and compared to verify the model can widely use in different locations.

2) Supply chain cost model. The supply chain cost model for different methods based on time study in specific time period and locations, thus it is different for regions and skills of workers, meanwhile, with technologies development, models would be changed with more time efficient vehicles appear. In further research, to evaluate supply chain cost in different regions, time study should be taken firstly to build their own supply chain cost model.

3) Kemera subsidy system. Kemera subsidy system is varied with different policies, and only valid in Finland, thus location policies about subsidy should be known in the further research.

4) Energy production model. Four plants were selected in this work for case study, unfortunately limited performance and cost for different unit capacities, especially CHP plant were missing in this work. In further research, more cost data for different capacities in different regions should be added to evaluate.

5) Optimization model. A dynamic model was applied in this work, it associated with numerous parameters and can be evaluated in different ways. In further research, different supply chain with different material should be added to compare, meanwhile, based on this model, different storage land and plant locations could be considered to make optimization supply chain in spatial and temporal distributions.
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APPENDIX I - OPTIMIZATION MODEL CODE

Part I mode code

//parameters
//two machine roadside storage supply chain

int m = ...;
int n = ...;

range harvest = 1..m; // harvest period, month
range storage = 13..n; // storage period, second year, month

float EC0 = ...; //Net Calorific Value at 0% MC (GJ/t)
float rho0 = ...; //Basic density (kg/m3)
float rhob = ...; //bulk density (kg/m3)

// parameter from excel file *******************
float rho[harvest][storage] = ...; //density define
float MC[harvest][storage]=...;
float EC[harvest][storage] = ...; // EC, GJ/t
float DML[harvest][storage] = ...; // dry matter loss, %, 1% per month

float ED[storage]=...; // plant energy requirement per month

// HC_ harvest; ST_storage; CH_ chipping; TR_transpot;
float HC[harvest][storage]=...; //€/m3 solid,
float OT[harvest][storage]=...; //€/m3 solid other cost include storage cost
float CH[harvest][storage]=...; //€/m3 solid
float TR[harvest][storage]=...; //€/m3 solid

float minMC=...; //%
float maxMC=...; //%

float alpha=...; // solid to loose volume ratio;
//variables*************

dvar float+ X[harvest][storage]; //solid volume, m3

dvar float+ Xs[harvest][storage]; //solid volume after storage, m3, intermediate variable
dvar float+ MMC[harvest][storage]; //total MC weight at plant,kg
dvar float+ Volume_storage[1..25]; //harvest volume per storage time

//results generated to excel file
dvar float+ Volume_total; // total volume to plant
dvar float+ ED_total; //total energy content, MWh
dvar float+ HC_total; // total HC cost
dvar float+ OT_total; // total OT cost
dvar float+ CH_total; // total CH cost
dvar float+ TR_total; // total TR cost

//expressions******

dexpr float cost= sum (i in harvest, j in storage) Xs[i][j] *(HC[i][j]+OT[i][j]+CH[i][j]+TR[i][j]);

// model ****************

minimize cost;

//constraints ***********

subject to
{
    //intermediate variable define****************
    forall(i in harvest, j in storage: j>=i) Xs[i][j]=X[i][j]*(1-DML[i][j]);
    forall(i in harvest, j in storage: j>=i) MMC[i][j]=Xs[i][j]*rho[i][j]*MC[i][j];

    Volume_total= sum (i in harvest, j in storage) Xs[i][j]; // solid volume, m3
    ED_total= sum (i in harvest, j in storage: j>=i) Xs[i][j] *EC[i][j]*rho[i][j]/1000 *0.277; //unit, MWh 0.277 GJ to MWh

    HC_total= sum (i in harvest, j in storage: j>=i) Xs[i][j]*HC[i][j];
    OT_total= sum (i in harvest, j in storage: j>=i) Xs[i][j]*OT[i][j];
    CH_total= sum (i in harvest, j in storage: j>=i) Xs[i][j]*CH[i][j];
    TR_total= sum (i in harvest, j in storage: j>=i) Xs[i][j]*TR[i][j];
    forall(k in 1..24)
        Volume_storage[k]= sum(i in harvest, j in storage: j-i==k-1) X[i][j];

    //*************************************************************
forall(j in storage)
  monthly_energy_demand: //*****************************************************************************
  sum (i in harvest;j>=i) Xs[i][j] * EC[i][j]* rho[i][j]/1000 >= ED[j]; // GJ per month

forall(j in storage)
  MC_requirement: //MC weighter averageMC is mass percent******************
  minMC* sum (i in harvest;j>=i) Xs[i][j]* rho[i][j] <= (sum (i in harvest;j>=i) Xs[i][j]* rho[i][j] * MC[i][j]);

forall(j in storage)
  (sum (i in harvest;j>=i) Xs[i][j]* rho[i][j]*MC[i][j]) <= maxMC* sum (i in harvest;j>=i) Xs[i][j]* rho[i][j];

forall(i in 1..m-1)
  even_production: //*****************************************************************************
  sum (j in storage;j>=i) Xi[i][j] == sum (j in storage;j>=i) Xi[i+1][j];
}

Part II Data Code

*******************************************************************************
* OPL 12.9.0.0 Data
* Author: guangxuan wang
* Creation Date: Sep 9, 2019 at 4:17:07 PM
*******************************************************************************

//constant*******************************************************************************
m = 24;
n = 24;
alpha = 2.5;

EC0 = 19.1; // Net Calorific Value at 0% MC (GJ/t)
rho0 = 377; // Basic density (kg/m3)
rhob = 275.8; // Bulk density (kg/m3)

// moisture content constraint default 0.3-0.45
minMC = 0.3;
maxMC = 0.45;

// from excel file*******************************************************************************
SheetConnection my_sheet("SCcost.xls");
MC from SheetRead(my_sheet, "MC_CPLEX");
EC from SheetRead(my_sheet, "EC_CPLEX"); // net calorific value
rho from SheetRead(my_sheet, "density_CPLEX"); //density

DML from SheetRead(my_sheet, "DML_CPLEX");
ED from SheetRead(my_sheet, "ed_cplex");

// SC price
HC from SheetRead(my_sheet, "HC_CPLEX");
OT from SheetRead(my_sheet, "OT_CPLEX");
CH from SheetRead(my_sheet, "CH_CPLEX");
TR from SheetRead(my_sheet, "TR_CPLEX");

// Export data
X to SheetWrite(my_sheet,"volume_harvest_cplex");
Xs to SheetWrite(my_sheet,"volume_storage_cplex");
MMC to SheetWrite(my_sheet,"mmc_cplex");
Volume_storage to SheetWrite(my_sheet,"month_storage_cplex");

cost to SheetWrite(my_sheet,"total_cost_cplex");
Volume_total to SheetWrite(my_sheet,"total_volume_cplex");
ED_total to SheetWrite(my_sheet,"total_energy_cplex");
HC_total to SheetWrite(my_sheet,"Harvest_cost_cplex");
OT_total to SheetWrite(my_sheet,"Other_cost_cplex");
CH_total to SheetWrite(my_sheet,"Chipping_cost_cplex");
TR_total to SheetWrite(my_sheet,"Transport_cost_cplex");
APPENDIX II. USERFORM GENERATED BY VBA