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Improving strategic decision-making with simulation based decision support systems

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SUMMARY

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Combating climate change is one of the key tasks of humanity in the 21st century. One of the leading causes is carbon dioxide emissions due to usage of fossil fuels. Renewable energy sources should be used instead of relying on oil, gas, and coal. In Finland a significant amount of energy is produced using wood. The usage of wood chips is expected to increase in the future significantly, over 60 %.

The aim of this research is to improve understanding over the costs of wood chip supply chains. This is conducted by utilizing simulation as the main research method. The simulation model utilizes both agent-based modelling and discrete event simulation to imitate the wood chip supply chain. This thesis concentrates on the usage of simulation based decision support systems in strategic decision-making. The simulation model is part of a decision support system, which connects the simulation model to databases but also provides a graphical user interface for the decision-maker.

The main analysis conducted with the decision support system concentrates on comparing a traditional supply chain to a supply chain utilizing specialized containers. According to the analysis, the container supply chain is able to have smaller costs than the traditional supply chain. Also, a container supply chain can be more easily scaled up due to faster emptying operations. Initially the container operations would only supply part of the fuel needs of a power plant and it would complement the current supply chain. The model can be expanded to include intermodal supply chains as due to increased demand in the future there is not enough wood chips located close to current and future power plants.

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Ilmastonmuutoksen torjunta on yksi ihmiskunnan keskeisimmistä kysymyksistä 2000 –luvulla. Yksi pääasiallisimmista syistä on fossiilisten polttoaineiden käyttäminen, minkä takia uusiutuvia luonnonvaroja tulisi käyttää öljyn, maakaasun ja hiilen sijasta. Suomessa merkittävä osuus energiasta tuotetaan puun avulla. Puuhakkeen käyttö tulee lisääntymään tulevaisuudessa merkittävästi, yli 60 %.

Tämän tutkimuksen tavoitteena on parantaa ymmärrystä liittyen puuhake-toimitusketjujen kustannuksiin. Tämä analyysi on toteutettu käyttäen hyödyksi simulointia. Malli käyttää hyödyksi sekä agentti- että tapahtuma-pohjaista mallinnusta toimitusketjujen mallintamisessa. Tutkimus keskittyy simulointipohjaisten päätöksenteon tukisysteemien hyödyntämiseen strategisessa päätöksenteossa. Simulointimalli on osa päätöksenteon tuen järjestelmää, joka yhdistää mallin tarvittaviin tietokantoihin mutta sisältää myös graafisen käyttöliittymän.

Järjestelmän avulla verrataan perinteistä puuhake-toimitusketjua toimitusketjuun, joka käyttää hyödyksi erikoiskontteja. Analyysin mukaan kontteja käyttävän toimitusketjun kustannukset ovat pienemmät kuin perinteisen toimitusketjun. Tämän lisäksi kontteja käyttävä toimitusketju on helpompi laajentaa käsittelemään suurempia volyymejä johtuen nopeammasta tyhjennyksestä. Alkuaan kontit otettaisiin käytettäväksi perinteisen toimitusketjun rinnalle, jolloin voimalaitoksessa olisi kaksi rinnakkaista toimitusketjua puuhakkeen hankkimiseksi. Simulointimalli on mahdollista laajentaa käsittelemään intermodaalisia kuljetuksia, koska kasvaneesta kysynnästä johtuen tulevaisuudessa puuhaketta ei ole riittävästi saatavilla voimalaitoksien lähellä.

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1 Introduction

1.1 Background

Global warming is arguably one of the key problems of humanity in the 21st Century. According to Sims et al. (2007) one of the key measures to combat climate change is to switch energy production towards renewable sources. At the moment, most of the energy (about 80%) in the world is produced from fossil fuels (Sims et al. 2007). The situation is though better in Finland as about 45% of the energy is currently being produced from oil, coal, and natural gas (Official Statistics of Finland 2012a). The historical development of energy sources in Finland is presented in Figure 1.

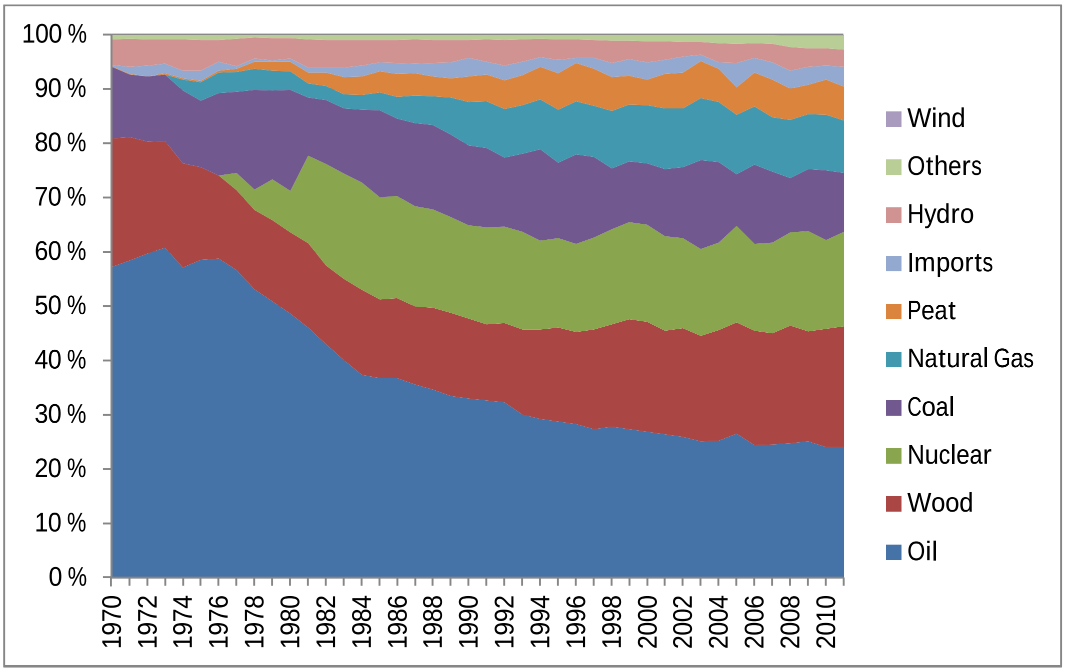

Figure 1: Energy sources used in Finland (Official Statistics of Finland 2012a)

The greenhouse gas emissions in Finland have been relatively stable since the beginning of 1990. The total amount is a little bit over 70 million tons of CO_2 equivalent emissions (Official Statistics of Finland 2012b). However, Finland should decrease CO_2 emissions by 16% in 2020 compared to 2005 (Jalkanen et al. 2008). According to Kirkinen (2010), fuels derived from forest residues have a small environmental impact compared to other sources (peat, reed canary grass, natural gas, and coal). As such, forest residues should be a central theme in Finnish energy policy in the future.

According to Ylitalo (2012), in 2011 7.5 million solid cubic meters of wood chip was used in heat and energy production. In 2020 this amount should increase to 12 – 13 million solid cubic meters. There are many improvement areas in wood chip procurement and supply chains (Laitila et al. 2010). Two of these are: improving the efficiency of chipping and transportation, and improving wood chip procurement business. Improving the productivity and profitability of wood chip supply chains will have a large impact on the total costs of the supply chains. According to Ihalainen and Niskanen (2010), the average price for heat production in a CHP-plant is 43.10 € / MWh for dried wood chips and 44.73€ / MWh for fresh wood chips. According to Karttunen et. al. (2010) the total costs of the supply chain could be in optimal logistics about 18 €/MWh for forest chip material made of small-sized trees using roadside chipping system and 50 km hauling. This is similar to the total delivery costs at the factory (18.1 € / Mwh) presented in BioEnergia (2012). As such, about 40 % of the costs related to heat production come from the cost of the supply chain.

Choosing the appropriate strategy to collect the wood chips is an important decision for a power plant and has a high impact on the costs of the operations (Ihalainen and Niskanen 2010). Strategic investments are usually difficult to estimate (Chevalier-Roignant et al. 2011) and novel decision support is needed to make good decisions (Gorry and Scott Morton 1971; Power 2002). Well conducted decision processes will yield significantly better results, especially if analytical methods are used (Dean and Sharfman 1996). As new innovations are appearing in the bio-material business, choosing the correct technology is a vital task (Christensen and Bower 1996). As such, achieving a sustained competitive advantage is a difficult task (Barney 1991; Dierickx and Cool 1989; Teece et al. 1997).

This thesis is part of a larger TEKES project called “Intermodal transportation concept for forest chips”. The project has five major research tasks: improving the financial aspect of wood chip transportation, practical demonstrations, improving logistics and business models, estimating environmental benefits, and modelling of the logistical system. The transportation concept is based on utilizing specialized containers.

1.2 Research problem

The research problem of this thesis is the financial feasibility of different kind of wood chip supply chains and the first main research question is: *“What are the chipping and transportation costs of wood chip supply chains?”* The research question can be further divided to sub research questions. The sub research questions are: *“What are the most important cost drivers in different kinds of supply chains?”*, *“How does moisture content impact the supply chain costs?”*, and *“How does advanced filling technology impact the supply chain costs?”*. The sub question help answer the main research question. The aim of this study is to be able to provide guidelines to choosing the correct amount and type of trucks to supply enough wood chips for a power plant.

The second main research question considers the actual decision-making process: *“How can simulations improve decision-making when considering new technological options?“*. This research aims to improve current understanding on the usage of simulation based decision support systems.

In this research the point of view is a financial one. The study disregards other aspects, such as environmental effects, from the analysis. Also, the study concentrates on strategic decision-making. The impact of operational policies and tactical decisions are not analyzed, only the impact of having different amount of trucks in the supply chains. The study also takes a full supply chain point of view and does not differentiate between potential organizations in the supply chain. It is assumed that none of the actors take a profit margin from their operations. Also, the study only concentrate on the chipping and transportation operations and the model does not include the cost of the actual wood or the processing costs at the power plant.

1.3 Research strategy

This research corresponds with the “modelling of the logistical system” part of the larger TEKES-project. This task relies heavily on the other tasks as they generate some of the data used in the model. Also, many studies (Karttunen et al. 2008; Karttunen et al. 2010; Korpinen et al. 2011; Korpinen et al. 2012) and a survey (Karttunen et al. 2012) have been conducted before this project and they work as the foundation for the simulation model. This is presented in Figure 2.

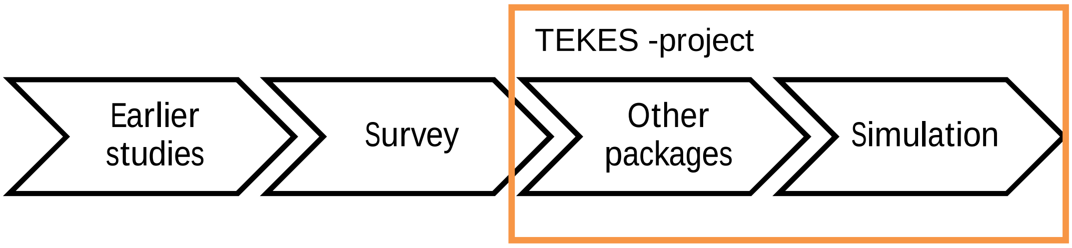

Figure 2: Research process

Data for this study has been gathered from many sources. These include expert interviews (personnel with experience in wood chip supply chains), a survey (largest machinery manufacturers and largest operators), and an estimate on wood availability (conducted by using a Geographical Information System). Figure 3 shows how these different data sources are connected to the simulation model.

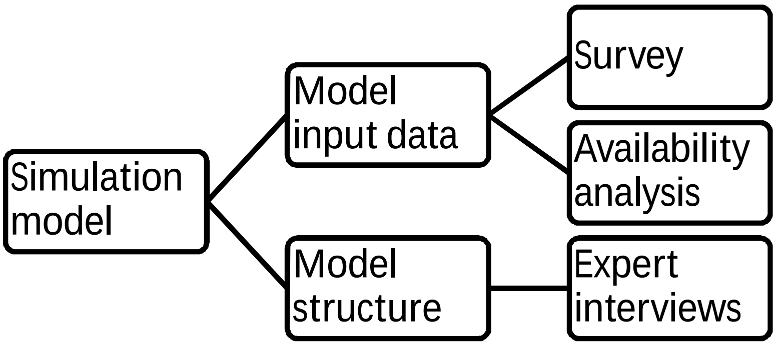

Figure 3: Simulation model and data sources

This research utilizes a case study approach and the case study is based on a power plant located in Central Finland which uses peat and wood chips to generate both electricity and heat. As the purpose is to estimate the costs of a supply chain instead of giving an optimized solution, simulation was the appropriate method. The simulation model will give a descriptive analysis of the different types of supply chains.

Simulations can be seen to follow critical realism (Mingers 2000) and as such, the models are assumed to be only an imperfect understanding of reality. Simulation models can also be either axiomatic or empirical (Bertrand and Fransoo 2002). Axiomatic research concentrates on idealized models while empirical models try to make the model to fit empirical data. Simulation research can also be divided to descriptive and normative models. As this study is mainly descriptive and empirical, the chosen approach is descriptive and empirical modelling, which can also be called nomothetical research according to the Neilimo and Näsi (1980) framework.

1.4 The empirical analysis

The empirical analysis of this thesis compares two different kinds of supply chains, one using traditional, fixed solid frame trucks while the other one uses trucks carrying specialized containers. The specialized containers are based on an innovation of a Finnish company (Fibrocom Oy) and currently only few of the actual containers exist. As such, it is not possible to conduct extensive studies using the real system.

In this thesis the chipping and transportation costs of the supply chain are considered. The whole supply chain costs also consists of the cost of the actual physical wood paid to the owner of the forest, felling and logging, accumulating the wood for transportation after felling, and transportation within the forest (Laitila et al. 2010). The simulation model is used only to analyze the chipping and transportation operations as the operations before chipping do not differ between different types of trucks.

Simulation was chosen as the approach as the problem is highly stochastic and dynamic, which makes other approaches difficult to use. The simulation model itself utilizes multiple simulation approaches together as different approaches support each other. The model is then connected to a decision support system, which will allow managers to make informed strategic decisions regarding the wood chip supply chain.

With the decision support system five different kinds of analyses are conducted. The first analysis is a base case, which is the main analysis. Three of the other analyses (compression technology, moisture content, sensitivity analysis) are needed to analyze the sub research questions while the fifth analysis (expanded operations) analyzes a very likely future scenario.

1.5 Structure of the research

This thesis is structured as follows. Section one provides an introduction to the topic, as well as the research question and used methodology. The second section provides a literature review about strategic decision-making and decision support systems. In this section the literature about strategic-decision making, decision support systems, and simulations is summarized. The third section contains the actual empirical case study. This section contains the overview of the decision support system, structure of the simulation model, and the results of the simulation model. The fourth section provides the discussion regarding the empirical study while the final section contains the conclusions and provides further avenues of research.

2 Simulation based decision support systems in strategic decision making

2.1 Simulation based decision support systems

Decision-making is one of the central activities of managers. One of the seminal works in decision-making is Simon’s (1960) framework, where he analyzed different types of decision according to their programmability. Programmable problems have a pre-defined method how the problem can be solved while non-programmable problems do not. Anthony (1965), on the other hand, analyzed planning and control system from the perspective of the level of the decision. Decision can either be strategic planning, tactical control, or operational control. Later Gorry and Scott Morton (1971) combined these two frameworks together and created an Information Systems framework. As such, the type of the system will depend on the programmability of the problem, as well as, the level of the decision. Examples of these are presented in Table 1.

Table 1: Information Systems framework (modified from Gorry and Scott Morton 1971)

	Operational Control	Management Control	Strategic Planning
Structured	Order Entry	Short-Term Forecasting	Warehouse Location
Semi-Structured	Inventory Control	Variance Analysis	Mergers and Acquisitions
Unstructured	PERT	Sales and Production	R&D Planning

Decision Support Systems (DSS) is a subset of Information Systems. DSSs, as their name implies, aid to improve managers during decision making. The first ones started to appear in the 1960s (Power 2002). According Courtney (2001), there are seven phases in the DSS decision-making process. This is presented in Figure 4. The process begins with the problem recognition. This can happen in many different ways and during this stage managers become informed about a problem. After the recognition, it is necessary to define the actual problem. The problem definition might take many different forms and will also depend on the type of problem according to the Gorry and Scott Morton (1971) framework.

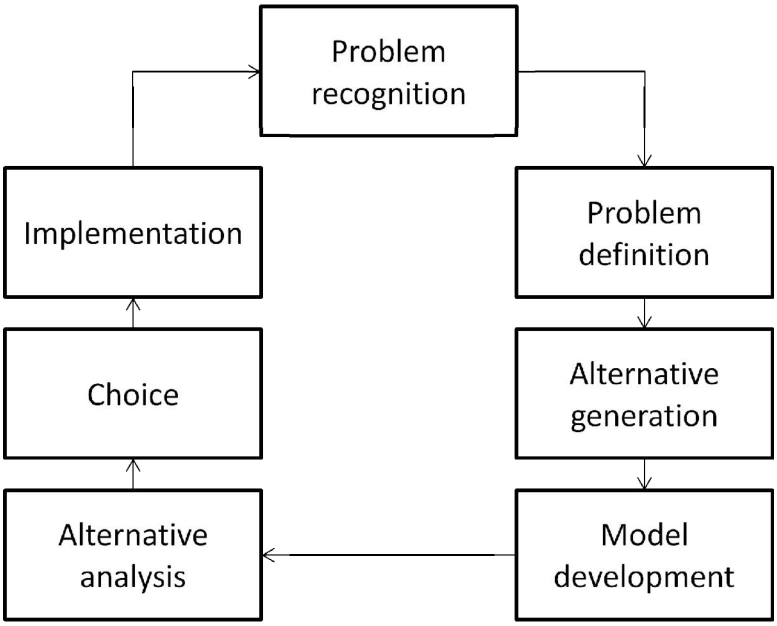

Figure 4: The decision support system decision-making process

After the problem definition it is possible to generate different alternatives. In order to compare these alternatives, different types of models are developed. The models are then used to compare the different alternatives. The models can be some kind of mathematical models which are then optimized and the decision-makers would then analyze the different alternatives. After the analysis is complete, the managers need to make the actual choice. The decision might consist of multiple criteria, in which case the actual mathematical models might have difficulties with. Finally the managers are responsible for implementing the actual choice. This then feedbacks to problem recognition and starts the process again.

There are many different kinds of DSSs. According to Power (2002) the possible DSS components can be classified to five categories. The first category, communications-driven DSS, concentrates on improving communication and collaboration. These usually utilize some sort of group DSS. Group DSS remove communication barriers, provide structured decision analysis and directs the discussion systematically (DeSanctis and Gallupe 1987). The second type of DSS is data-driven. Data-driven DSS are systems which help manager monitor operational performance or gather intelligence from historical data (Power 2008). Usually these DSS gather data from multiple sources and provide an overview of the situation to the manager. The third kind of DSS is document-driven. In document-driven DSS the focus is on handling large amount of different kinds of documents and providing retrieval and analysis techniques (Power 2002). The fourth kind of DSS is knowledge-driven. Knowledge-driven DSS usually utilize some sort of artificial intelligence to recommend specific actions to managers (Goul et al. 1992). The final DSS is a model-driven DSS. In model-driven DSS the system contains some type of a mathematical optimization or simulation module (Power and Sharda 2007).

According to Robinson (2004, p. 4), simulation can be defined as “Experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and / or improving that system”. There are many keywords in the definition. Experimentation means that various kinds of tests will be conducted with the model. Simplified imitation intends that the simulation model is only a very simplified view of the actual systems. It imitates the system but various generalizations have been made. An operations system defines the boundaries of the model. According to Forrester (1968) systems can either be open or contain feedbacks. Feedback systems are closer to simulations as the past behavior of the system usually has an impact on the future performance of the system. This is also evident from the definition as it discusses the progression through time. Finally, the definitions points out the purpose of better understanding or improvement of the system. Simulation in itself is descriptive; it only tells how the system behaves. The improvement can be done by using some sort of Design of Experiments (some recent examples include Longo 2010, and Bottani and Montanari 2010) or by optimizing the heuristics of the model (Ivanov 2009).

In a recent literature Jahangirian et al. (2010) analyzed the usage of simulation in business and manufacturing. The four most widely used methods are: discrete event simulation, systems dynamics, hybrid models, and agent-based modelling. Discrete event simulation concentrates on individual events. Usually this is done with the help of servers and queues (Banks et al. 2005). In these systems different entities move from server to server and wait to be serviced at queues. This type of a system is presented in Figure 5.

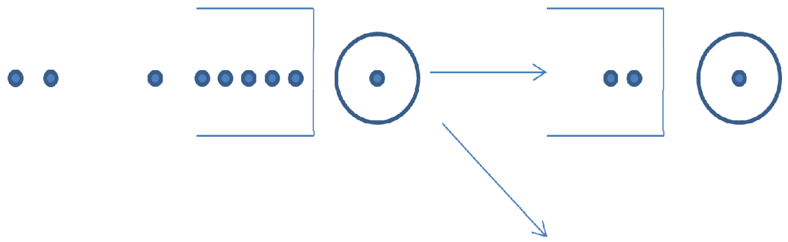

Figure 5: An example of server and queue structure

System dynamics, on the other hand, concentrates on high level structures and the connections between different parts of the structure (Sterman 2000). These models mostly contain various differential equations, which are able to represent the connection between the elements. The actual modelling uses stock and flow diagrams to represent the structure. Stocks are different kind of accumulations (like machinery, cash, orders, etc.) while flow elements move entities between different stocks. An example of this is presented in Figure 6.

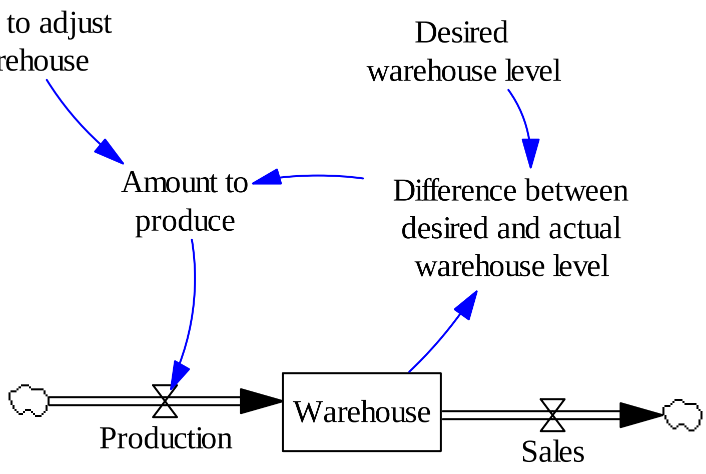

Figure 6: Example of stock and flow diagram

Hybrid models combine two or more different simulation methods to one model and it is not a modelling approach in itself. The fourth approach, agent-based modelling, is a relatively new paradigm in simulations. In agent-based modelling the central focus is on individual agents, who interact with other agents (Macal and North 2006). Some basic properties for agents have been presented (Wooldridge and Jennings 1995). These are: autonomy, social ability, reactivity, and pro-activeness. The agents do autonomous actions, are able to interact with other agents, react to perceived changes in the environment, and finally are goal-directed. Figure 7 shows an example of an agent-based model where there are two larger groups of agents and a coordinator, who all make local decision in order to achieve their own goal.

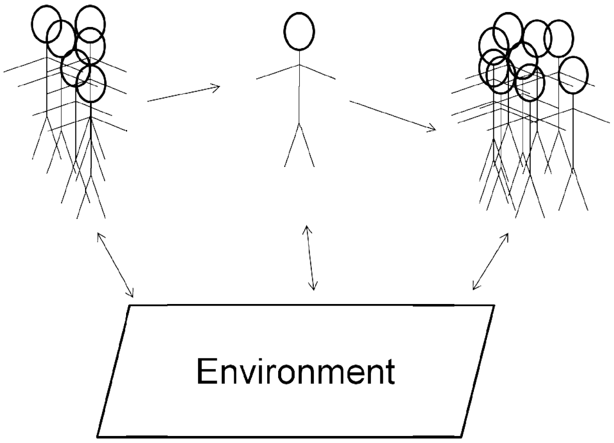

Figure 7: Example of Agent-based modelling

Simulations are frequently used in decision-support systems. Some recent examples include analyzing the evacuation of individuals with disabilities (Manley and Kim 2012), evaluating a carsharing network's growth strategies (Fassi et al. 2012), comparing environmental impacts of a supply chain (Jaegler and Burlat 2012), integrating manufacturing and product design into supply chain network reconfiguration (Kristianto et al. 2012), and risk management (Fang and Marle 2012).

2.2 Strategic Decision Making

The fundamental question in strategic management is how firms achieve and sustain competitive advantage (Teece et al. 1997). According to Hamel and Prahalad (1993) competitive advantage is achieved by leveraging the core competences of the organization and stretching the current resources towards an aspiration. This point of view uses resources as the main approach to achieve competitive advantage. According to Barney (1991), competitive advantage is achieved by utilizing VRIN resources (Valuable, Rare, Imperfect imitability, and Non substitutable) which exists due to resource heterogeneity at the firm level. Dierickx and Cool (1989) point out, that these types of resources are not readily available in the market place and must be developed. This development requires time and at the same time, assets tend to erode which makes competitive advantage more difficult to sustain. The ability to create new resources (dynamic capabilities) then becomes an important routine (Teece et al. 1997).

Technological change can be a difficult challenge to even capable organizations (Christensen and Bower 1996). At the deeper level the technological change is difficult due to investments. According to Huisman and Kort (2003), technology investment is especially difficult due to uncertainty related to better technologies which will be invented later. Also, as organizations rarely operate in a monopolistic environment, it is difficult to estimate the impact of first-mover advantage. Investments opportunities can also be seen to be real options (Luehrman 1998). Some investment might have a negative net present value, but due to uncertainty, they might become more profitable in the future. According to Chevalier-Roignant et al. (2011) there are seven factors which organizations need to take into account when devising investment strategies under uncertainty: static competitive advantage, first- versus second-mover advantage, complete versus incomplete information, size of capacity increments, capacity utilization and returns to scale, number of competitors, and completion delays. Overall it can be stated that the investment decisions are difficult to handle.

According to Eisenhardt and Zbaracki (1992) there are three different views on strategic decision-making: rationality and bounded rationality, politics and power, and the garbage can model. In bounded rationality decision-makers pursue a common direction using rational decision-making. On the other hand, in politics and power different people have different interest and due to different bargaining positions the direction of the organization will move according to the will of powerful coalitions. In the garbage can model organized are more chaotic and decision-makers use trial-and-error learning and thus, the final choices will also depend on luck. Eisenhardt and Zbaracki (1992) synthesize that organizations are political systems with conflicting objectives, which managers try to achieve with bounded rationality.

Schwenk (1995), on the other hand, approached strategic decision making from three different research streams and compared these against three newer topics. The research streams are: strategic decision modeling, individual and organizational minds, biases in strategic decision making, and upper echelons. The first stream, strategic decision modeling, concentrates on creating models of actual strategic decision. The second stream, individual and organizational minds, concentrates on the mental images of the decision-makers. This is achieved by providing cognitive maps of various strategic problems, competitive conditions, etc. The third stream, biases in strategic decision making, was originally studied by cognitive psychologists. In this stream the various biases and their implications for decision making are analyzed. The final stream, upper echelons, concentrates on the characteristics of those individuals, who are responsible for formulating strategy. These studies mainly concentrate on the CEO and the other members of the top management team.

Schwenk (1995) provides also three newer topics, which should be incorporated to the four traditional streams. The first topic, strategic decision making and information technology, concentrates on the usage of information technology as part of strategic decision making. The second topic, competitive strategic decision-making, combines strategic decision-making with the field of competitive strategy. The third topic, international strategic decision-making, concentrates on the differences between decision-making in different environment. The research potential of different streams and topics is presented in Table 2.

Table 2: Research potential in strategic management (Schwenk 1995)

	Strategic Decision Making	Individual and Organizational Minds	Biases in Strategic Decision Making	Upper Echelons
Strategic Decision Making and Information Technology	High	Moderate	Moderate	High
Competitive Strategic Decision Making	Moderate	High	High	Moderate
International Strategic Decision Making	High	Moderate	High	Moderate

According to Dean and Sharfman (1996) the actual decision processes have an important role in the quality of decisions. Managers collecting information and using analytical techniques make more effective decisions than other managers. As such, utilizing more advanced decision-making methods should improve the quality of the decisions.

2.3 Framework used in the thesis

The theoretical framework of this study uses multiple views. These are presented in Figure 8.

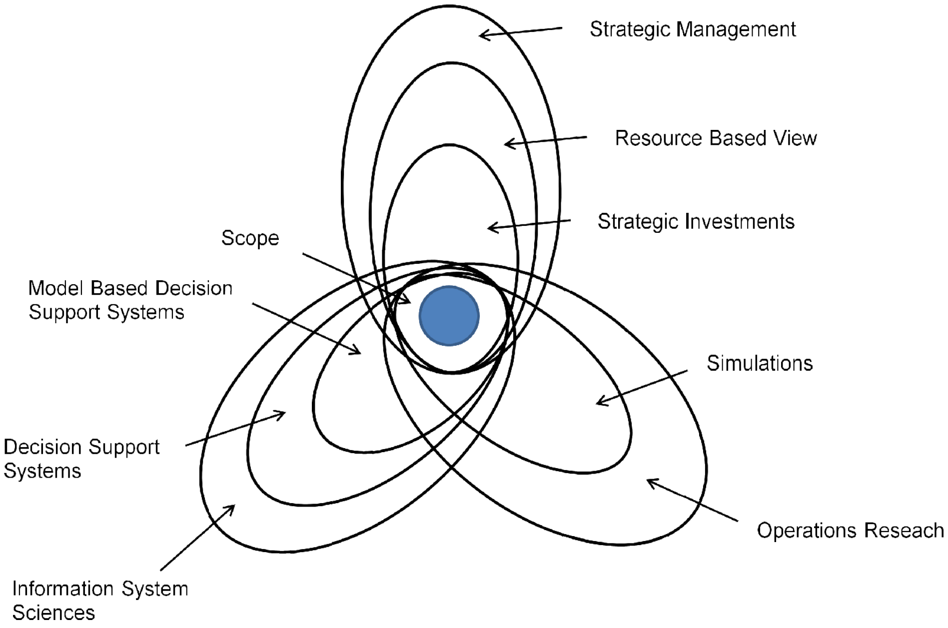

Figure 8: Connections between main theoretical concepts

This thesis concentrates on strategic decision-making from the perspective of rationality and bounded rationality (Eisenhardt and Zbaracki 1992). As such, in this thesis it is assumed that politics and power do not have any impact on the decision and the organization uses the best possible method to come up with the decision. The methodology utilizes advanced simulation systems, which should provide more reliable results than non-analytical methods (Dean and Sharfman 1996). The decisions use a resource based view (Barney 1991) and the main area of interest is strategic investments (Luehrman 1998). The model can be seen to be part of a DSS (Section 2.1) and the DSS is model-driven (Power 2002). The system can be seen to be a structured one as the user has very limited capability of modifying the actual simulation model. The user can analyze the problem using different parameters (Section 3.2.1), but the actual method remains the same. As such, the DSS is a structured one. The actual strategic decision considers investing into a new technology. This can be seen to be an option (Luehrman 1998) based analysis, as there are significant uncertainties involved with the decision. Overall, the thesis utilizes information technology in decision-making (Schwenk 1995).

3 Empirical analysis – A simulation model for bio-fuel supply chain

3.1 Background

In this research the case study is based on a real power plant, which uses wood chips and peat as its power source. At the moment the wood chips are transported to the power plant with solid-frame trucks. Most of the solid frame trucks have a chain system, e.g. the cargo space is emptied by opening the back door and then chains in the cargo space starts to rotate. This rotation moves the material towards the back of the truck and finally the cargo “drops” from the truck. The purpose of this research is to compare a strategic alternative for the wood chip supply chain. Recently a Finnish organization (Fibrocom Oy) has developed a new type of a container. These containers use a special channel composite structure, which allows the containers to be lighter than traditional solutions. This allows the containers to have more payload than a solid-frame truck. However, these containers need some kind of emptying systems to empty the payload at the power plant.

The simulation model is part of a larger TEKES-funded project. LUT Savo Sustainable Technologies has for many years studied different types of bio-fuel supply chains (Karttunen et al. 2008; Karttunen et al. 2010; Karttunen et al 2012; Korpinen et al. 2011; Korpinen et al. 2012). The current project, “Intermodal transportation concept for forest chips”, builds on top of the earlier projects and utilizes advanced analysis methods to estimate these different types of supply chains. As it was discussed in Section 1.1, the usage of wood chip is estimated to increase up to 75% during the next eight years. There are large business opportunities available in the bio-fuel industry in Finland and choosing the right strategic alternative will yield significant advantages.

3.2 Methodology

As the purpose of the study is to compare different kinds of alternatives, simulation was chosen as the approach. The simulation model has been constructed by using a simulation software called Anylogic. The actual simulation model combines both agent-based modelling (ABM) and discrete-event simulation (DES) together. The reason to use multiple approaches was to have the versatility of ABM but also utilize the server structures of DES. In addition to the simulation model, the system uses external data and contains a graphical user interface.

In this section the connectivity of the simulation model is presented first. Then we discuss the external data, which was collected for the simulation model. Thereafter the structure of the simulation model is presented. Then the used cost model and parameters are introduced, and finally the model outputs are presented, and validity and reliability discussed.

3.2.1 Connectivity of the simulation model

The simulation model contains a graphical user interface (GUI) which connects the actual simulation model to the decision-maker. The decision-maker cannot make any changes to the simulation model, but (s)he can modify parameters, which have an impact on the actual simulation model. The simulation model then runs according to the chosen parameters and ultimately the simulation model gives output data to the GUI. The GUI presents the results to the decision-maker with the help of different types of charts. The system is presented in Figure 9.

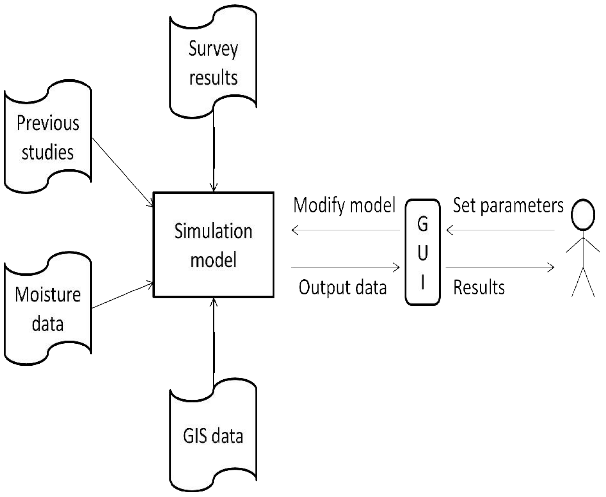

Figure 9: General structure of the decision support system

A lot of data has also been collected in order to make the results of simulation model more reliable. The model uses data from a survey, a GIS analysis, earlier research projects, as well as data regarding actual moisture contents of wood chips in a power plant.

The GUI contains parameters which the user can directly modify. It would be possible to have all of the parameters in the GUI, but this would make the model too complicated for the decision maker. The parameters which the manager can change are presented in Table 3.

Table 3: Parameters available in GUI

Parameter	Value
Amount of trucks	0...X
Type of truck	Container or traditional
Type of rotator	Mobile or fixed
Compression used	Yes or no

The amount of trucks is an integer number. It should be noted, that technically the manager could have as many trucks as possible, but this should also have an impact on the distance. This is still ongoing work to improve the feedbacks within the system. The rest of the parameters are simple dichotomous decision, e.g. truck is either a container truck or a traditional truck.

3.2.2 External data sources

The simulation model utilizes one database file, which is derived from an availability analysis (Korpinen et al. 2012). This analysis was conducted by using a Geographical Information System (GIS). The GIS analysis was based on availability of forest fuels at the municipal level and land-use data. In addition to this, competition in the area was also taken into account. The location of the power plant was used as the main location and in the GIS analysis the purpose was to minimize the driving distance while obtaining a specific amount of biomaterial for the power plant. The actual output data has driving distances as well as the amount of bio-material available in over 1000 different points close to the power plant. This is presented in Figure 10.

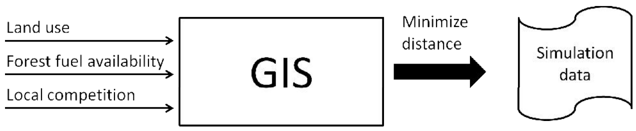

Figure 10: Simulation data obtained through GIS analysis

The amount of energy available in bio-material is heavily dependent on the moisture content. This also has an impact on the payload of the trucks as well. Due to these reasons it was important to have reliable data regarding the moisture content of bio-material. According to Alakangas (2000), the average moisture content in Finland is between 40 to 45 %. However, in daily operations the moisture content varies between 30 to 60%. For the simulation model the power plant provided actual data for moisture content during different months. The actual values are presented in Figure 11.

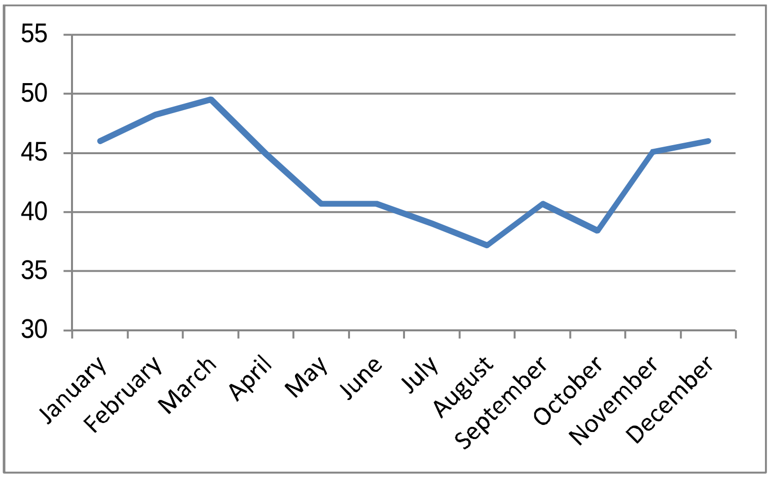

Figure 11: Moisture content during different months

A lot of parameters will have an impact on the results. Karttunen et al. (2012) conducted a survey where various wood chip and peat suppliers and machinery manufacturers were questioned. In this study the actual amounts of transported material, types of trucks, size of payload, the utilized emptying systems, as well as tare weight were explored. The results of the survey and cost analyzes were then used as the parameters for the simulation model.

3.2.3 The structure of the simulation model

As it was stated in Section 3.2, the simulation model utilizes both ABM and DES principles. The main elements in the model are trucks and they have been modeled by using ABM. The reason to choose ABM was to have enough versatility as the trucks need to represent the actual operations relatively accurately in order to have reliable results. In addition to trucks, the model contains the main terminal. This terminal has been modeled using DES principles. We will first present the truck agents and then the actual terminal operations.

The truck agents have five different states: waiting at depot, moving to location, being filled, being emptied, and being out of service. The state chart is presented in Figure 12. The out of service represents the situations when the trucks are not used due to lack of shifts. In the real systems the trucks do not operate three shifts each day; they operate two shifts from January to April, one shift in May and June, no shifts during July and August, one shift from September and October, and again two shifts from November till December. It is important to have the correct amount of shifts as the fixed costs are relatively high in this environment.

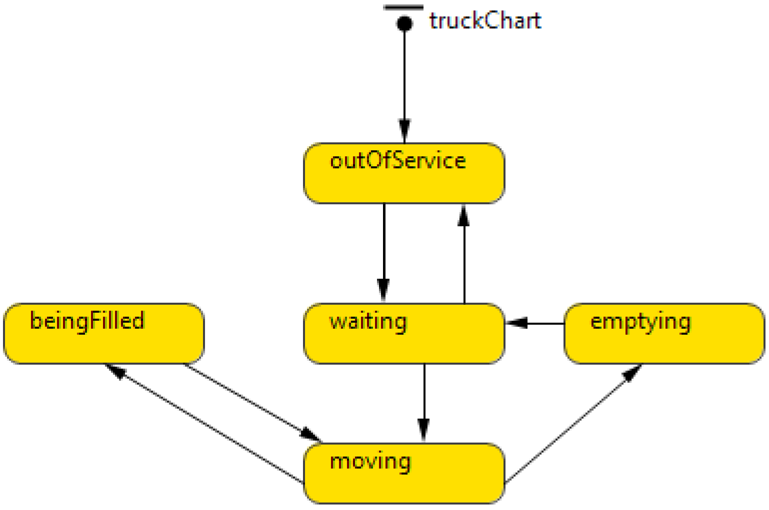

Figure 12: Statechart of the truck –agent

When a new shift starts, the truck moves to the “waiting” state. In this state the truck checks whether it has enough time to can go and pick up a load, bring it back and empty it before the shifts ends. The trucks are allowed to work overtime for a certain amount (one of the parameters in the model). If the truck does not have enough time, it will simply wait for its shift to end.

When a truck finds a load, it will move to the “moving” state. During this state the truck will move between locations. If the truck is empty, it will move to a roadside chipping location. On the other hand, if the truck is full it will move to the main terminal. During this step the trucks keep track of how much tonkilometers were generated. This depends both on the weight of the truck, as well as the weight of the cargo.

When the truck arrives to the chipping location, it is getting filled. The filling time follows a stochastic distribution (triangular distribution). When the truck is full, it will head back to the main terminal. The truck will again move into the “moving” state until it arrives to the terminal. When the truck arrives to the main terminal, it will move to the “emptying” state.

When the truck moves to the “emptying” state, it actives the main terminal. The trucks will have to wait for some time before they are emptied. This waiting depends on the amount of trucks which are at the terminal, as well as the type of truck and emptying equipment is available. The flowcharts for these operations are presented in Figure 13 and Figure 14. Again, the waiting times are important as fixed costs are relatively high.

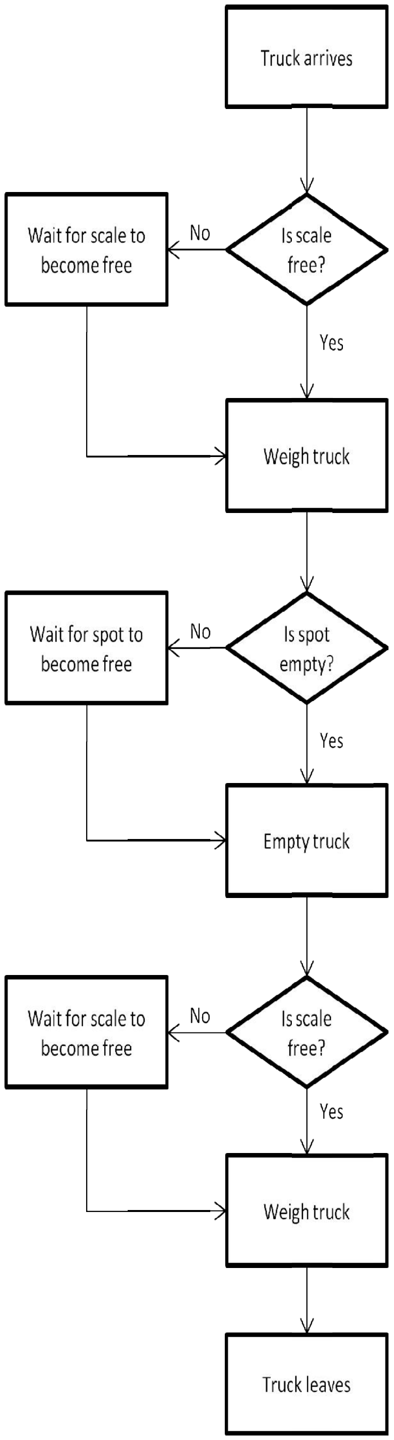

Figure 13: Flowchart for traditional truck terminal operations

When traditional trucks are used, the operations include a weighing. This is needed in order to know the amount of the bio-material on board. Also, during the scaling operations other important issues are also taken care of, such as paper work. These are not needed when the trucks use containers as the weighing operation can be done with the rotator.

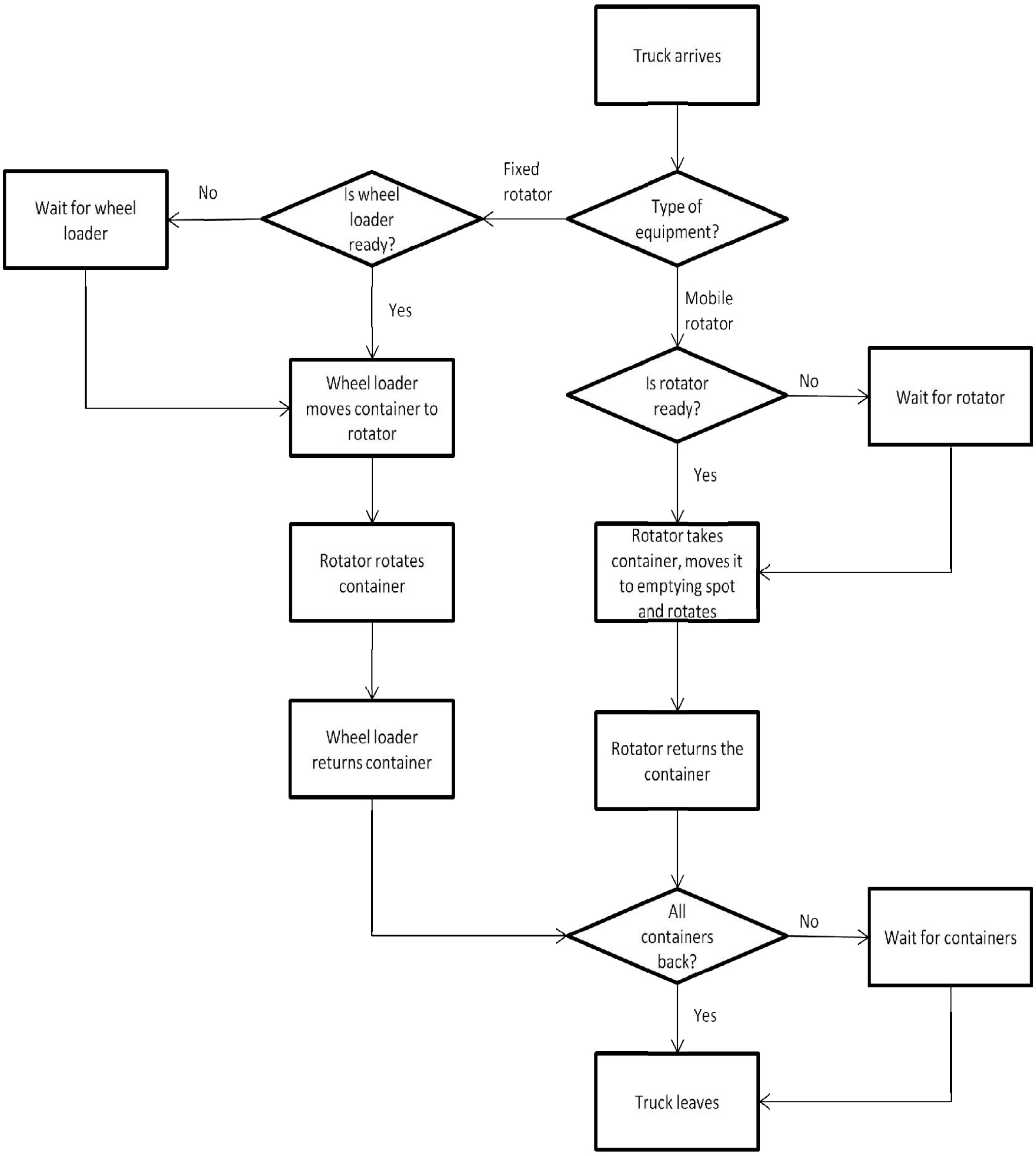

Figure 14: Flowchart for container truck terminal operations

When the truck leaves the terminal, it moves again to the “waiting” state. Again, the truck checks whether it can pick up a load or not and then decides, whether to move to the “moving” state or not.

3.2.4 The cost model

In the simulation model costs are divided to two different categories: fixed and variable costs. As the names imply, the fixed costs are fixed at the truck, chipper, and rotating device level, while the variable costs depend on the actual occurred operations. Simulations benefit greatly by this division as it is possible to calculate the actual amount operations occurring and they are not dependent on assumptions. The values for the cost model are presented in Table 4.

Table 4: Values used in the cost model

		Value	Scale
Chipper	Fixed	285000	€ / a
	Variable	3	€ / tn
Truck, traditional	Fixed	86000	€ / a
	Variable	0,01235	€ / TKm
Truck, container	Fixed	83000	€ / a
	Variable	0,01235	€ / TKm
Rotator, fixed	Fixed	57519	€ / a
	Variable	11,04	€ / rotation
Rotator, mobile	Fixed	67400	€ / a
	Variable	25,79	€ / rotation

The fixed costs also include the actual investments. The mobile rotator has an amortization time of five years while a fixed rotator has 10 years. This makes the mobile rotator much more expensive than the fixed rotator. The fixed costs for container trucks are also smaller than the costs for the traditional trucks as the containers have an amortization time of 20 years compared to seven years of the actual trucks. The actual values used in the simulation model are based on earlier studies (Karttunen et al. 2012).

One chipper can normally serve two trucks. However, if the distance between the chipper and main terminal increases, it is necessary to increase the amount of trucks as driving takes a relatively larger share of the total time. The chipper is the most expensive piece in the supply chain and it has especially large fixed costs per year.

3.2.5 Parameters used in the study

The model contains a lot of different parameters. As was stated in Section 3.2.1, a lot of the parameters were derived from a survey. In addition to the survey, some of the data has been developed during earlier research projects (Karttunen et al. 2010; Korpinen et al. 2011). Some of the most important ones are studies regarding payload, energy content, and moisture level of the cargo. When a truck goes and picks up a load, the simulation model randomizes the moisture content of the load using the yearly fluctuation as the base line. The moisture of the cargo will impact the total weight of the truck. The used values are presented in Figure 15.

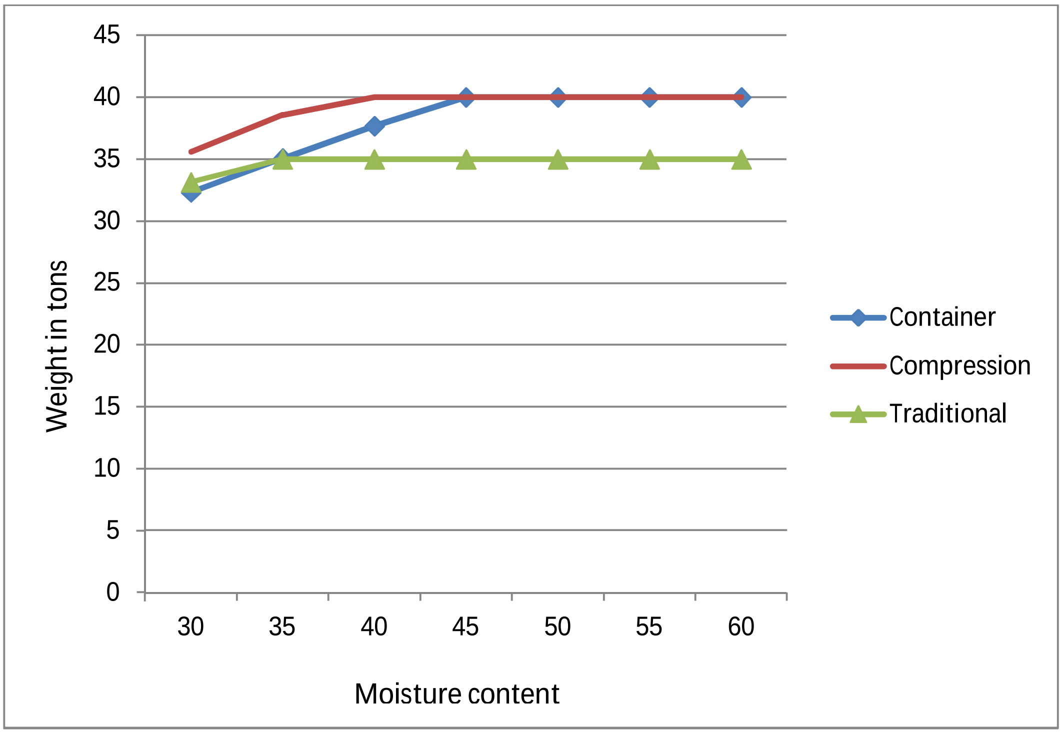

Figure 15: Impact of bio-material moisture content on payload weight

As it is possible to notice from Figure 15, the container truck has a higher payload than a traditional truck when the moisture content is higher than 35 percent. The container truck is 5 tons lighter than a traditional truck and due to this reason it can have heavier payloads than a traditional truck. When the moisture content rises, the trucks are limited by the total weight of the truck and payload (weight limit in Finland is 60 tons). However, when the moisture content is small, the payloads are limited by the volume of the frame. The volume of three containers is a little bit smaller than the volume of traditional truck and this is why traditional trucks are more beneficial than containers when volume is the only restricting factor. However, as it was stated in Section 3.1, the containers can also benefit from compression. If compression is used, it is possible to remove the air out of the cargo, which makes it possible to have more room for the actual material in the container instead of air. This increases the amount of bio-material to be transported when the moisture content is low.

The weight of the cargo in itself only impacts the amount of tonkilometers which the trucks generate while driving between locations. What is more important is the actual amount of energy available in the payload. The higher the moisture content, the smaller amount of bio-material is available by volume and at the same time, a lot of energy is wasted during the conversion process. This is presented in Figure 16.

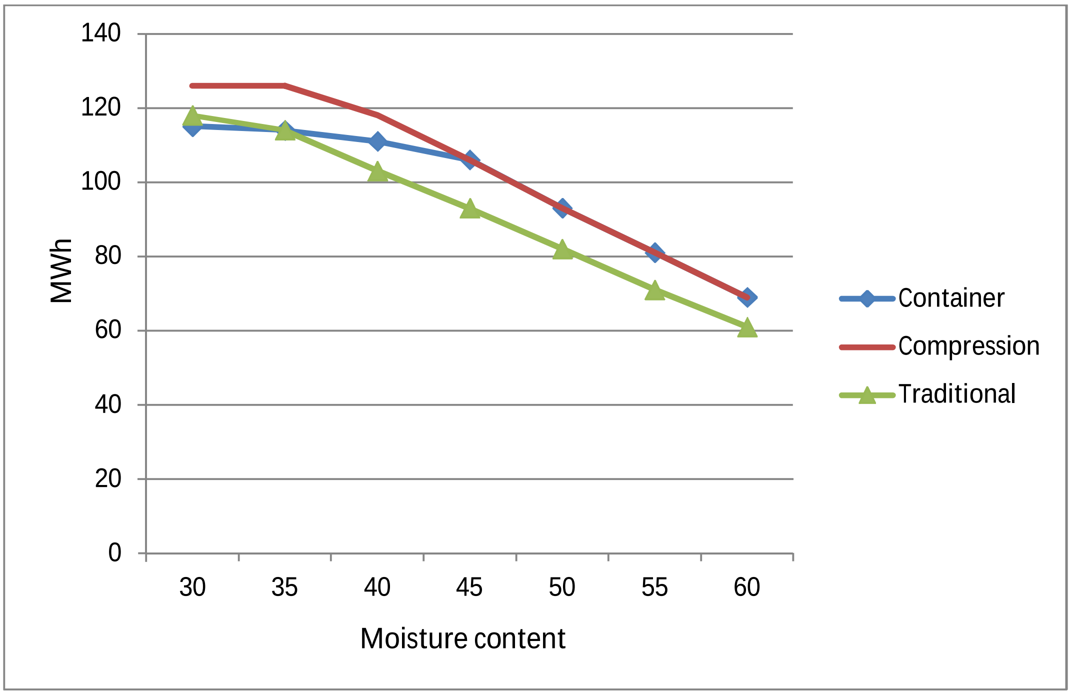

Figure 16: Impact of bio-material moisture content on available energy

The energy content clearly corresponds with the weight of the truck. Traditional truck has more energy when the moisture content is 30 percent, but in all other cases container trucks are more beneficial. Also, then the moisture content is below 45 percent, the compression gives additional benefits. As the amount of shifts is highest between January and April and November and December (discussed in Section 3.2.3), and during these months the moisture content is on a higher level (Figure 11), the container trucks should have on average a higher amount of energy content in the payload compared to traditional trucks.

In addition to the weight and energy content of the cargo, there is a wide variety of parameters. Most of these parameters impact the actual operations, e.g. it impacts how the trucks operate in the simulation model. These are presented in Table 5.

Table 5: Parameters used in the model

Parameter		Value	Scale
Minimum filling time	Container	50	minutes / truck
	Traditional	50	minutes / truck
Maximum filling time	Container	80	minutes / truck
	Traditional	80	minutes / truck
Minimum emptying time	Fixed rotator	5	minutes / container
	Mobile rotator	5	minutes / container
	Traditional	20	minutes / truck
Maximum emptying time	Fixed rotator	7	minutes / container
	Mobile rotator	7	minutes / container
	Traditional	30	minutes / truck
Additional time	Container	10	minutes / truck
	Traditional	10	minutes / truck
Allowed overtime		120	minutes
Tare weight of truck	Container	20	tn
	Traditional	25	tn

Many of these parameters were based on the survey of Karttunen et al. (2012). However, the variables concerning the container trucks are only educated guesses. This is because currently there are no real supply chains using the containers and the machinery is currently being constructed.

3.2.6 Model outputs

In order for the simulation model to be useful, it needs to have meaningful outputs. The results of the model need to be summarized, preferably using different kinds of plots and charts. Also, visualization is also frequently used to verify the model as well as to improve communication over the model. The simulation model contains five different kinds of summarized variables. These are presented in Table 6.

Each one of the analyses serves a specific purpose. The time usage is used to understand where the trucks spend their time in different scenarios. This is also closely related to rotator utilization. If the utilization is low, it indicates that the power plant could handle a larger amount of trucks without problems. The time usage should also reflect the driving distance. When the driving distances increase, there should be an impact on the time usage as well.

Table 6: Simulation model outputs

Variable	Type of analysis
Time usage	Pie chart
Cost analysis	Stack chart
Rotator utilization	Bar chart
Driving distance	Histogram
Weekly collection	Time plot

The weekly amount of collected bio-fuels is also important for the decision-maker. As there is some kind of cyclicality in the operations (due to different amount of shifts), it is important to know how much material is available during different time of the year. The final variable is the actual cost analysis. This is most likely the most important variable for the decision-makers. The decision whether to invest to new technology or not will depend on the financial feasibility of the solution. Also, the analysis separates different cost sources in order to provide more understanding on the problem domain. In addition to the variables, visualization is also provided. Example of this is presented in Figure 17.

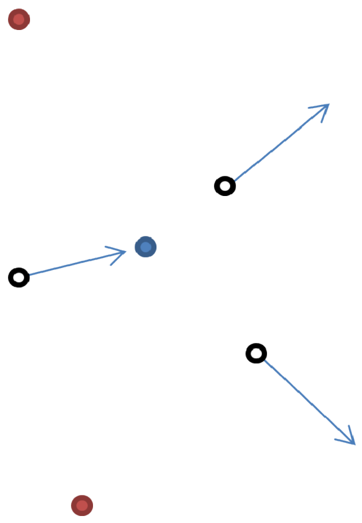

Figure 17: Visualization of truck movement

The visualization contains circles of different colors. Black circles with white filling are moving between locations. They are animated (move in the model) but for Figure 17 additional arrows have been added. When the trucks are being filled, their color changes to red. Also, when they are being emptied, they are of blue color.

3.2.7 Validity and Reliability

Validity and verifiability of simulation model is always a difficult task. Some authors argue (Sterman 2000) that the whole process of validation is impossible with simulations. Simulations are always based on mental models, which themselves are only impartial imitations of the system. However, the simulation model has been tested extensively to perform as it should in different kind of environments. This was done, for instance, by calculating how many trips a truck could do during one day when they were operating using two shifts. This gives justification in believing that the model is performing as it should be. Also, decision-makers need to make their decisions using some kind of a process and if simulations give the most accurate results (even if the results are wrong), it should be used in decision-making (Sterman 2000).

The reliability should be good as most of the data is based on based on earlier studies. However, if a different person would construct the simulation model, it would most likely differ heavily from the model used in this thesis.

3.3 The simulation model in action

In this section the simulation model is used to compare strategic alternatives as well as understand the sensitivity of the results. The main strategic alternatives are a supply chain based on traditional, solid frame trucks, and a new kind of supply chain utilizing a new technology, specialized containers. The initial analysis will compare these two types of supply chains and analyze the impact on the cost of bio-fuel.

Further analyses will expand the results of the initial analysis. In this phase the impact of moisture content will be analyzed. In the future it is expected that the amount of rain will increase (Jylhä et al. 2009). This will also have an impact on the moisture content of bio-fuels. If one of the alternatives looks more beneficial in future climate, it gives further justification in choosing over that specific option.

The third analysis will concentrate on the size of power plant. As the demand for wood chip based energy production increases in the future, it is possible to expand the current operations to handle a larger amount of bio-fuel. This will also increase the length of driving distance from the power plant to the road side chipping points, as there is not enough wood available anymore closer to the power plant.

The final analysis will examine the sensitivity of the used parameters. The parameters will be allowed to vary according to certain criteria and the purpose is to identify the variables which have the largest impact on results. This will help the decision-maker to focus on the key variables in order to have more reliable results from the simulation study.

3.3.1 Base scenario

The base scenario uses the actual parameters and values which were discussed in Section 3.2. In the container supply chain a fixed rotator was chosen as the costs are lower and it is currently under construction. The rotator will be used in a demonstration where one of the containers is used to see how fast the flipping operation can be performed. The current estimates used by the model are based on initial analyses, but currently no actual machinery exists.

In the base scenario the power plant requires about 540 GWh of bio-fuels each year. From the availability analysis it was calculated that this would require an average range of 80 kms from the power plant to gather the required amount of wood chips. The distance has an impact on the amount of trucks required as a longer distance will require longer driving time. If more material is required, the distance needs to be increased, as well as the amount of trucks. The simulation model was tested using various amounts of trucks to see what amount would be able to satisfy the requirements of the power plant.

In order to collect at least 540 GWh of bio-fuels, it requires 12 traditional trucks. This amount of trucks is able to gather 580 GWh while 10 trucks gather 500 GWh. For the container trucks the required amount if 10 trucks (600 GWh). With 8 container trucks the amount collected equals to about 480 GWh. For the base case 12 traditional trucks and 10 container trucks are used. The reason to use an even number of trucks is due to the chippers. It would not be realistic to have a chipper serving only one truck.

In order to have meaningful results from the model, the total costs of the supply chain will be divided with the total amount of energy delivered. This is the normal way to represent costs in this environment. Results from the base case are presented in Table 7. As it is possible to notice from Table 7, most of the costs are generated by the fixed costs of the truck and the chipper. Either the trucks and chippers need to have high utilization or costs will be too high. Also, the traditional supply chain is about 15% more expensive than the container supply chain. This gives strong justification to invest more resources to conduct additional analyses on the container supply chain in order to have more accurate results. In order to understand the cost advantage, the time usage of the trucks needs to be analyzed. This is presented in Figure 18.

Table 7: Base case cost comparison

Type of cost	Container	Traditional	
Truck fixed costs	3,07	3,92	€ / MWh
Truck variable costs	0,666	0,794	€ / MWh
Chipper fixed costs	2,392	2,978	€ / MWh
Chipper variable costs	1,126	1,164	€ / MWh
Rotator fixed costs	0,097	0	€ / MWh
Rotator variable costs	0,32	0	€ / MWh
Total	7,671	8,856	€ / MWh

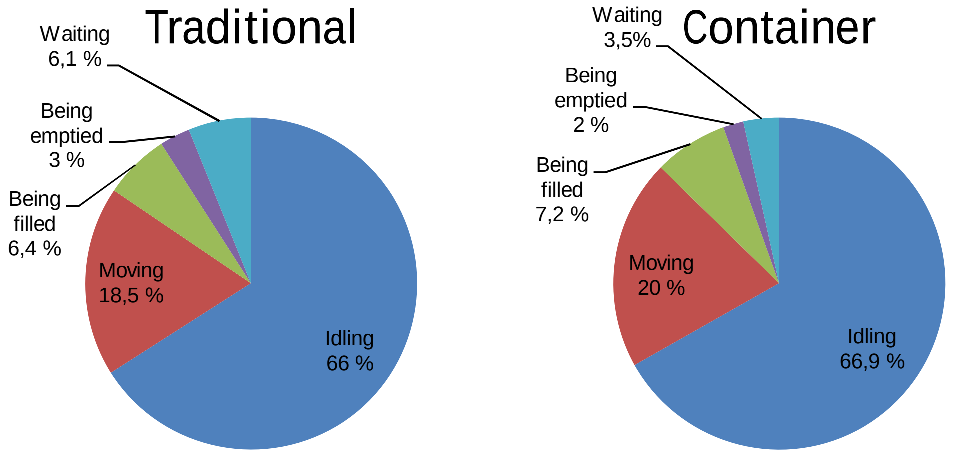

Figure 18: Pie charts for truck time usage

Trucks spend most of their time idling at the terminal. This is due to the shift restrictions and the model also takes the day of the week into account (no work is done during Saturday or Sunday). One big difference between the systems is the emptying and waiting times. The traditional trucks spend 9,1% of their time in these activities while the container trucks spend only 5,5% of their time. As there is a smaller amount of trucks and the emptying is faster, the container trucks do not need to spend that much time waiting to be emptied. This allows the trucks to spend more time moving or being filled. The container trucks have a higher amount of idling and this is most likely due to the fact that the container trucks end their days earlier while the traditional trucks need to wait for emptying.

It is also important to understand the amount of incoming bio-fuels during different times of the years. The material can be easily stored, but it is important that the inventories stay high enough through the whole year. Figure 19 shows the collected wood-chips for the container truck supply chain.

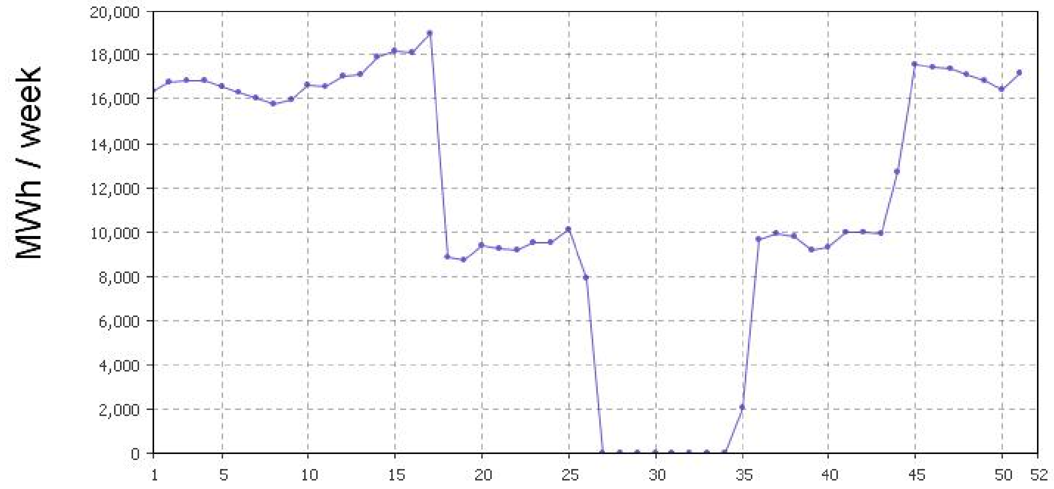

Figure 19: Total amount of wood-chips delivered per week (MWh / week). The y-axis shows the current week in the model

As it is possible to notice from the figure, the amount of collected bio-fuels is highly dependent on the amount of shifts (discussed in Section 3.2.3). Also, it is possible to notice that the average moisture content also has an impact on the results. The collection peaks during April before the trucks start to operate again using only one shift. The trucks collect the most material while the moisture content is highest.

The base case provides a lot of important information for the decision-makers. It is cheaper to utilize containers in the supply chain compared to current, traditional options. The difference occurs due to decreased waiting and emptying times, which allows more time to be spent on moving and filling. Finally, the collection will peak during April and will then slow down for the summer.

3.3.2 Using compression technology

During earlier studies it has become clear that it would be possible to use an innovative system where excess air is sucked out of the container, which allows transporting more wood-chips in the actual container. Figure 15 and Figure 16 presented the estimates for the impact of moisture content on the filling rates and energy content when using compression. The base case will now be run with the same parameters but this time the container trucks are able to use the compression technology. Table 8 shows the cost related to the supply chain when using compression.

Table 8: Supply chain costs when using compression

Type of cost	Compression	
Truck fixed costs	2,997	€ / MWh
Truck variable costs	0,656	€ / MWh
Chipper fixed costs	2,338	€ / MWh
Chipper variable costs	1,123	€ / MWh
Rotator fixed costs	0,094	€ / MWh
Rotator variable costs	0,314	€ / MWh
Total	7,522	€ / MWh

The costs of the supply chain utilizing compression are similar to the costs of the container supply chain. The compression technology allows having lower costs in the supply chain. However, the cost difference is relatively small, only two percent. Most likely this is due to the fact that most of the cargo is collected during the most moist season, when the compression does not provide any benefits. Otherwise the results are almost identical. The only difference is that the compression supply chain provides 10 GWh more bio-fuels. The current analysis also does not have any costs associated with the compression technology. Some cost estimates are needed to in order to make final decision whether to invest in the technology or not.

3.3.3 Altered moisture content

The altered moisture content –analysis was conducted by using fixed moisture contents for the cargo. As it was stated in Section 3.2.2, the moisture content in Finland varies between 30 to 60 percent and as such, the analysis will cover this range. The range will be covered by using a step of five units, so the overall analysis will contain seven different comparisons. The results for this analysis are presented in Figure 20.

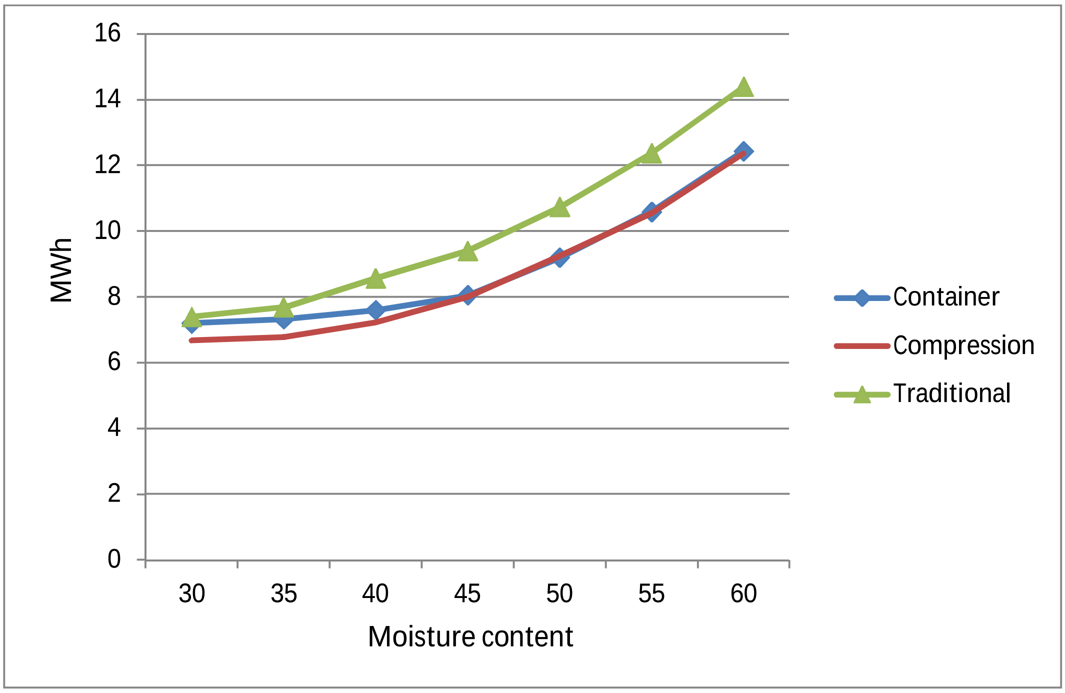

Figure 20: Impact of moisture content on price of bio-fuel

As it is possible to notice from Figure 20, the moisture content has a large impact on the results. As the average moisture content is expected to increase in the future, the containers become more feasible, even without the compression technology. Also, the container trucks are more profitable than traditional trucks in all cases. This gives strong justification in choosing the container technology over the traditional one.

The compression technology would provide good benefits if it would be possible to have wood chips with smaller moisture content. There are some technologies where a “blanket” is put on top of the wood residuals and this protects the material from rain. This allows the residuals to dry before both the residual and the “blanket” is chipped.

3.3.4 Expanded operations

The expanded operations case analyzes the impact of expanding the operations from the current power of 540 GWh to 740 GWh. In this case it is necessary to expand the maximum collection distance from 107 kilometers to 124 kilometers. This will again require more trucks, not only because of increased demand, but also due to the increased time spent on driving between the main terminal and the chippers. Again, the model was tested by using various amounts of trucks to see which amount is the “correct” one. For traditional ones 18 trucks are able to collect 700 GWh while 20 trucks are able to collect 750 Gwh. As such, 20 traditional trucks will be used in this scenario. On the other hand, only 14 container trucks are able to gather 740 GWh. This has a very high impact on the costs as well. These are presented in Table 9.

Table 9: Supply chain cost in expanded operations scenario

Type of cost	Container	Traditional	
Truck fixed costs	3,433	5,412	€ / MWh
Truck variable costs	0,77	0,924	€ / MWh
Chipper fixed costs	2,678	3,853	€ / MWh
Chipper variable costs	1,128	1,16	€ / MWh
Rotator fixed costs	0,077	0	€ / MWh
Rotator variable costs	0,32	0	€ / MWh
Total	8,406	11,349	€ / MWh

The costs for the container supply chain increase by 9,5%. This is a modest increase compared to the increase of 28% for traditional supply chain. In the expanded operations the traditional supply chain is 35% more expensive than the container supply chain. Further information can be achieved by analyzing the time usage of the trucks. These are presented in Figure 21.

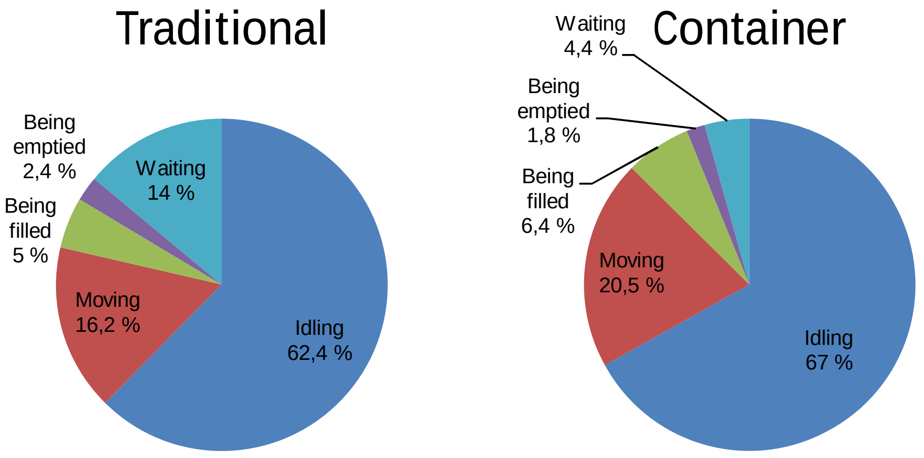

Figure 21: Pie charts for truck time usage in expanded operations scenario

As it is possible to notice from Figure 21, the traditional trucks spend 14% of their time waiting to be emptied. This is clearly a bottleneck for the traditional operations. For container trucks the time increases from 3,5% to 4,4%, which is a much smaller increase. As such, the expansion is more feasible when container trucks are used. For the traditional trucks it would be necessary to estimate how to increase the amount of slots for emptying at the power plant. This would most likely have a large impact on the results.

3.3.5 Sensitivity analyses

In the sensitivity analysis many parameters are given different kind of values in order to understand how this impacts the results. Most of the variables are estimates on earlier research projects, in which case the true values are not certain. For each of these variables two or three different values are used. The list of the variables and their range is presented in Table 10.

Table 10: Parameters used in sensitivity analysis

Variable	Values			Scale
Overtime	0	60	120	minutes
Interest rate	6	10	14	%
Average filling time	50	65	80	minutes
Average emptying time	4,5	6	7,5	minutes
Rotator investment	85000	110000	135000	€
Rotator variable costs	8,86	11,07	13,28	€ / rotation
Container amortization time	10	20		years

Overall almost 1500 simulation runs were run. In the simulation only the container supply chain was analyzed as all other scenarios have pointed towards the new technology. The results from the sensitivity analysis are presented Figure 22. Each one of the parameters will be now studied separately. It should be noted, that the average value for the simulations differs from the base scenario as more of the parameters have been scaled towards the negative side (for instance, only a smaller amount of overtime is analyzed).

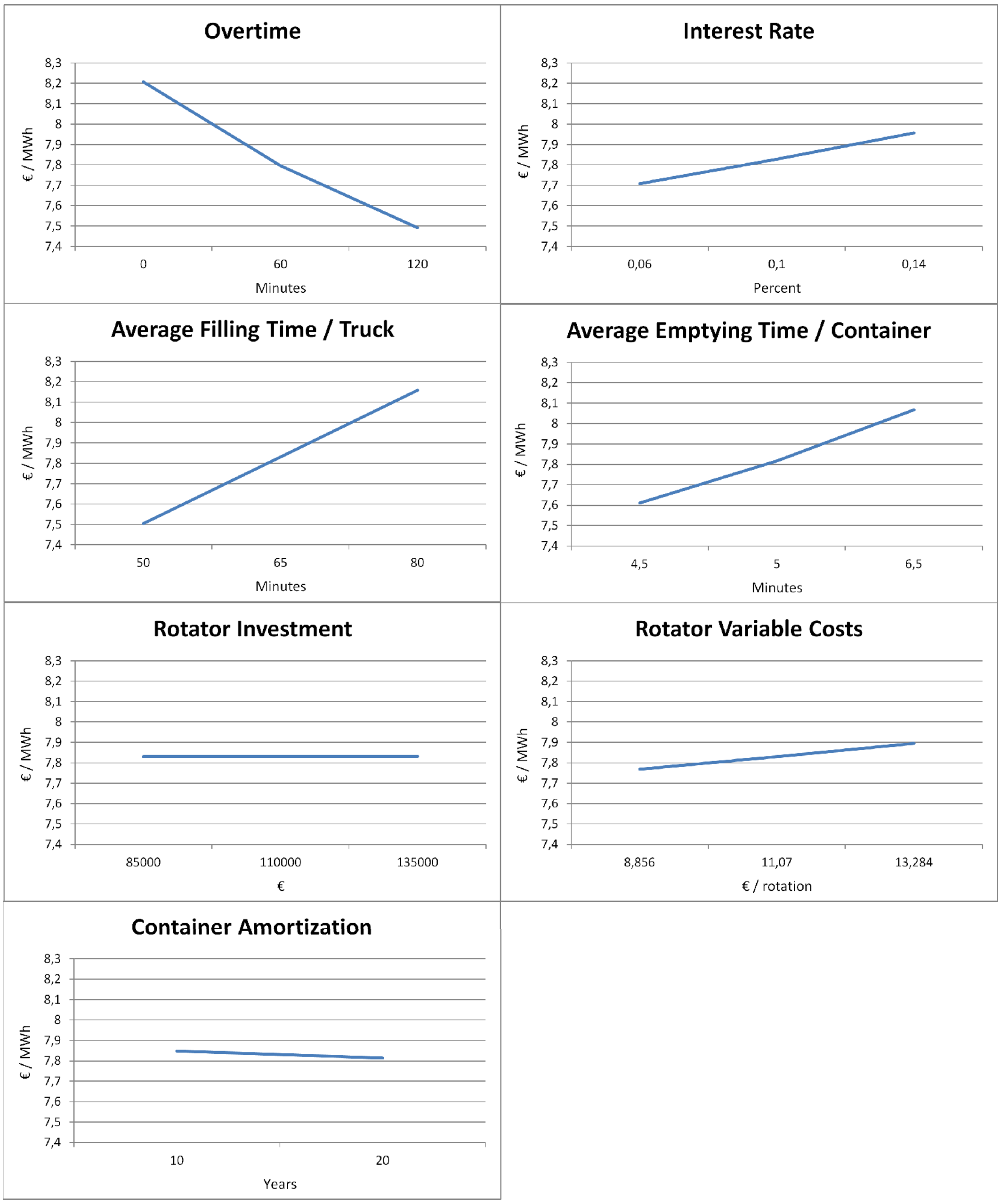

Figure 22: Impact of different parameters on the cost of bio-fuel

In the simulation model overtime has an impact on the condition whether a truck will go and pick up a cargo or not. Initially the overtime was set at 120 minutes, but 60 minutes was also considered. Also, we analyze the situation where overtime is not allowed. As it is possible to notice from Figure 22, the difference between the smallest and largest values is about 10% on the cost of the bio-fuel. The power plant needs to allow enough overtime. It should be noted, that at the moment the truck drivers do not get additional vacation days when they work overtime. This would have an impact on the results as the trucks would not be operating during each day.

The next variable to analyze is interest rate. The interest rate has an impact through the yearly annuity on investment. For a long time the interest rates have been relatively small, but in the sensitivity analysis it was allowed to grow to 14%. The interest rate clearly has an impact on the results, but overall the impact is a relatively small one. The difference between the smallest and largest values is 3,2%. So even in a high interest environment the profitability of the supply chain is not impacted by that much.

The filling time is the amount of time which the truck spends by the chipper being filled. The data for these operations is based on only a couple of cases and expert opinion. However, as it can be noticed from Figure 22, this variable has a large impact on the final results (8,7% difference between largest and smallest value). If the decision-makers need more accurate information about the final costs of the container supply chain, more accurate measurements regarding filling time need to be conducted.

On the other end of the supply chain the containers are emptied. As the rotating machine does not exist at the moment, the actual rotation times are only estimates. This variable also has a moderate impact on the results. The difference between the largest and smallest value is 6%. More accurate estimates for this variable are needed, as it only impacts the container supply chain.

On the other hand, the rotator investment has practically no impact on the cost of the supply chain according to the analysis. One rotator can easily handle a supply chain consisting of many trucks so the total investment is only a very small portion of the whole supply chain costs. Even the rotator variable cost have only a 1,6% difference between the smaller and larger value. This is also true for the container amortization time. The current estimates for the life-span of the containers is 20 at minimum, but even with a 10 year life-span the cost difference is less than 0,5%.

4 Discussion

Many different kinds of analyses were conducted in Section 3.3. The analyzes consisted of a base scenario, the usage of compression technology, impact of moisture content, a scenario with expanded operations, as well as sensitivity analyses. The purpose of different analyzes was to give a better understanding on the problem domain and thus, improve the quality of the decision whether or not to invest in the technology. The base case only contained one power plant while in reality there are two plants located nearby. This would have an impact on the availability analysis as well.

As it was noticed form the base case (Section 3.3.1), the container supply chain has a cost difference of about 15% compared to the traditional, fixed frame supply chain. The cost difference comes from meaningful time usage as well as better space utilization with most moisture contents (Figure 15 and Figure 16). Also, as it was noticed from the moisture content analysis (Section 3.3.3), the container supply chain is more feasible on all of the meaningful moisture values.

The moisture content analysis also pointed out, that a container supply chain backed up with compression technology would be very beneficial in the cases where the moisture content would be low. However, this would require some other technology as well because the amount of rain is expected to increase in the future (Jylhä et al. 2009). In addition to increased moisture due to additional raining, when demand increases and production scales up, the material will be fresher and this will further increase the moisture content. On the other hand, when using the compression technology, the cost of the supply chain will be about two percent lower when the cost of suppression is not taken into account (Section 3.3.2). This needs further studies as the cost difference is so small.

The cost difference starts to become large if operations are expanded (Section 3.3.4). The traditional, fixed frame supply chain will be severely constrained by the emptying operations. The overall supply chain cost difference is about 35%. If traditional trucks are going to be used, there needs to be modifications in the emptying yard. Otherwise the cost will increase significantly. It should be noted, that the container supply chain has lower costs in the expanded operations case than traditional trucks have with the base case.

The sensitivity analysis (Section 3.3.5) provides the final piece of information regarding the technology investment. The most striking results are the small impact of the life-span of the container, rotator investment, and rotator variable costs. There are large benefits associated with a shorter emptying time. If it is possible to have shorter rotations with higher investments, even with higher rotation costs, these should be pursued. It provides large dividends in the whole supply chain as it is possible to have more trucks operating in the same system and still the trucks do not end up waiting long times for the emptying operation.

It should be noted, that the simulation model assumes that the whole supply chain is operated with one type of a truck. In reality the container operations would slowly scale up and initially most of the supply chain would use the solid frame trucks. As it was noticed in the expanded operations scenario (Section 3.3.4), waiting times would rise significantly when traditional trucks are used. However, the container trucks could be used to expand the operations by having an additional emptying spot based on the containers. Also, by having two emptying spots and shorter waiting times, it is possible to increase the reliability of supplies, which is also a critical factor for the supply chains (Laitila et al. 2010). On the other hand, in this study the traditional trucks used values derived from a survey (Karttunen et al. 2012), not the latest potential which could be achieved. It would be possible to increase the payload of the traditional trucks by up to 6 tons with channel composite structure (Fibrocom Oy), in which case the traditional trucks would be able to carry more wood chip than the container trucks. The trucks have a larger space for the actual wood chips, but they would not fit that well on small roads. As such, flexibility would suffer.

5 Conclusions

5.1 Theoretical implications

The first main research question of this study was “*What are the chipping and transportation costs of wood chip supply chains?”* According to the simulation models the costs for the container wood chip supply is 7,671 € / MWh while the costs for a traditional supply chain is 8,856 € / MWh, a difference of 15 %. Comparing to the total costs of the supply chain (18,1€ / MWh according to BioEnergia 2012), the cost difference is 6,5% from total costs. The case analysis concentrated on a power plant with a demand of 540 GWh. The difference is about 640000 € on a yearly level. These cost savings would be divided between the involved organizations (chipper, trucker, and power plant). The power plant needs to invest more than the truckers, which makes the cost savings more difficult to divide among the organizations.

In addition to more detailed knowledge about the costs, sub research questions were also used. The first sub question *“What are the most important cost drivers in different kinds of supply chains?”* was analyzed also with the help of a sensitivity analysis. The fixed costs of the truck and chipper had the highest impact on the costs of the supply chain. This means, that the utilization of the trucks as well as the chipper needs to be high. According to the sensitivity analysis the fixed costs of the rotator and the amortization time of the container have almost no impact on the cost of the supply chain. On the other hand, the speeds of the emptying and filling operations have a high impact. The rotator should be designed to be as fast as possible, even if this increases the initial costs of the system. It should be noted, that the sensitivity analysis only covered a relatively small range and many other, different kinds of emptying solutions could have significantly higher initial investments.

Moisture content is also an important factor in the wood chip supply chain and the second research question was: *“How does moisture content impact the supply chain costs?”* The container supply chain was found to be cheaper to operate with any amount of moisture than the traditional supply chain. This gives further justification in using the container technology as the moisture content is most likely going to increase in the future when the operations scale up. The final research question *“How does advanced filling technology impact the supply chain costs?”* was analyzed with two different simulation sets. If the moisture content is low, the compression technology provides significant cost savings. However, this would require some kind of drying technology to achieve the benefits. In the base case simulation the compression technology lowers costs by two percent and those costs do not involve the actual costs of the compression technology. It is a potential option (Luehrman 1998), but at the moment it is too risky.

The second main research question was *“How can simulations improve decision-making when considering new technological options?“* The simulation model was inside of a DSS and the user could make only slight modifications to the model. It can be argued, that from the bounded rationality perspective (Eisenhardt and Zbaracki 1992) simulation based DSS work well. However, if the point of view would be more of politics and power, a group DSS might be a better option. The simulation based DSS is able to give multiple perspectives to the problem domain by modifying the parameters. This should remove uncertainty involved in the investment decision (Chevalier-Roignant et al. 2011). Simulations also perform well when estimating the financial impacts of different types of investments. Simulations allow naturally separating fixed costs from variable costs and give more accurate estimates about the total costs.

5.2 Managerial implications

This research provides many managerial implications. Firstly, logistics managers in the bio-fuel industry should look closely for the new technological innovation, as the costs of the supply chain will be 15% lower than with current average equipment. This is especially true if the power plant is going to be a large one and operations utilize economics of scale. The container trucks benefit heavily due to faster emptying times, which allows lower waiting times, as well as, higher truck utilization.

Secondly, in bio-fuel supply chains the speed of the emptying operations is much more important than the cost of the machinery. With the containers the actual size of investment had no practical implications on the cost of the supply chain. The companies might have lower cash flow initially, but the operations should be able to quickly create enough savings to justify the investment. Also, it can be possible that if the emptying operation is fast enough, there is no need to have that many trucks. This would again lower the costs of the supply chain and require less investments initially.

Thirdly, logistics managers should utilize simulation based DSSs in their operations. It is easy to conduct multiple kinds of analyses with this type of a system and have a better understanding of the problem environment. It is possible to understand which areas could benefit from some kind of a real option and gives information regarding the most sensitive parts of the operations. This can also be seen to be part of risk management.

5.3 Limitations and future research

The simulation model contains some limitations. The model does not take into account the differences between the container and traditional trucks in the narrow roads located in the forests. This might have some impacts on filling times. Also, at the moment the chippers are assumed to be available at the road side. In reality the chippers might not be available and there might be more waiting due to this. Also, the drivers do not need to balance their overtime in the model while in reality they need to take days off.

The further avenues of research include studying the difference between the traditional trucks and container trucks on the narrow roads. This could be done by doing actual, physical demonstrations and then utilizing that information as part of the simulation model. The model also should become chipper centered. At the moment they have not been modeled, but in the future a new agent should be included in the model. This would give more realistic results regarding the supply chain. It is also possible to include intermodal operations in the simulation model. As at the moment most material is gathered next to the actual power plant, with intermodal operations it would be possible to have “satellite” terminals to supply the power plant. This might be required in the future if competition intensifies for the raw materials.

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