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A framework for supply chain configuration of a biomass-to-energy pre-treatment process

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CHALMERS UNIVERSITY OF TECHNOLOGY

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ABSTRACT

A transition from fossil fuel to renewable energy sources such as biomass is an environmentally sustainable pathway. However, increased use of biomass is hampered by a number of barriers regarding movement of energy: through place, through time and through existing energy infrastructure. One means to overcome these barriers is to introduce a pre-treatment process such as torrefaction, which enhances the biomass product properties. In a supply chain perspective, there are a number of decisions to make regarding feedstock, supply system, torrefaction plant, distribution system, and customer demand. This renders a number of possible supply chain configurations. Hence, the purpose of this thesis is to understand the logistics implications of a pre-treatment process in order to propose supply chain configurations. This thesis is a compilation of four papers and the methods used are literature reviews, interviews and techno-economic modelling.

The major result of the thesis is a number of frameworks that can assist actors involved in configuration of torrefaction supply chains. First of all, biomass-to-energy supply chains without torrefaction were reviewed. The findings were classified into characteristics of the physical flow and further refined into three minor frameworks for supply chain configuration. Secondly, a framework for torrefaction configuration was developed, which entailed propositions on torrefaction configuration for three types of demand, represented by three customers: households, medium-sized bioenergy CHP and coal CHP. Finally, the cost of a feasible torrefaction supply chain under Swedish conditions was assessed. The optimal size of a torrefaction plant was calculated and a number of central parameters affecting supply chain cost and plant size were identified. In order to provide a foundation for evaluation in other cases, a framework describing the relation between torrefaction configuration and supply chain performance was proposed.

Keywords: Biomass-to-energy, supply chain, logistics, pre-treatment and torrefaction

List of appended papers

This thesis is based on four appended papers:

Paper I: Halldórsson, A, Svanberg, M (2013), "Energy resources: trajectories for supply chain management", Supply Chain Management: An International Journal, Vol. 18 Iss: 1, pp.66-73

Paper II: Svanberg, M "Factors influencing the biomass-to-energy supply chain configuration – the case of forest residues, An earlier version of this was published in Proceedings of the LRN Conference, 2011 University of Southampton, UK.

Paper III: Svanberg, M, Halldórsson, A (2013), "Supply chain configuration for biomass-to-energy: the case of torrefaction", International Journal of Energy Sector Management, Vol. 7 Iss: 1, pp.65-83

Paper IV: Svanberg, M, Olofsson, I, Flodén, J and Nordin, A, (2013), "Analysing biomass torrefaction supply chain costs", Bioresource Technology, Vol. 142, Iss: NA, pp.287–296

Contribution in each paper:

Paper I. I am the second author. My contribution is mainly regarding the biomass-to-energy literature review, and a minor contribution to planning and writing of the paper.

Paper II. I am the sole author of the paper.

Paper III. I am the main author of this paper. I developed the idea behind the paper, did the literature review and had the major responsibility in writing of the paper.

Paper IV. I am the main author of this paper. Model development and system design was done mainly by Ingemar Olofsson and me. I had the major responsibility for writing the paper, except for technical aspects.

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Terminology and abbreviations

- Refinement = A term for describing the transformation of low valued biomass to higher valued biomass.
- Production = A term used for describing the processes involved in refinement
- Pre-treatment process = A term describing a number of different processes for biomass refinement such as torrefaction, pyrolysis and steam explosion. In the biomass-to-energy literature and this thesis, the phrasing pre-treatment process is in general synonymous to all the activities of biomass transformation within the plant where the refinement takes place.
- Torrefaction = A thermochemical process for refinement of biomass.
- Torrefaction plant = A plant that contains a torrefaction process and almost always, a subsequent densification process.
- Process technology = The technological components that constitutes a torrefaction plant
- Densification = The process of turning biomass with high volume into a compact uniform low volume good, such as pelletising or briquetting
- TDB = Torrefied densified biomass, sometimes labelled torrefied pellets within the literature
- By-products = A product that is "waste" from forestry industry, e.g., sawdust or bark
- Forest residues = The branches and tops of a tree, sometimes labelled as forest waste, or forest slash
- Stemwood = The part of the tree that is the stem, e.g. not the branches, tops or the stump
- Supply chain configuration = Refers to decisions on the physical flow of biomass in terms of how components such as nodes and links are combined into networks for the physical flow of biomass.
- Torrefaction configuration = Refers to decisions regarding the organisation of production as well as upstream and downstream activities seen from the perspective of the torrefaction company
- Torrefaction supply chain = A biomass-to-energy supply chain containing a torrefaction plant
- Supply system = A part of the supply chain, in this thesis seen as the upstream part of the supply chain from the view of the torrefaction plant
- Distribution system = A part of the supply chain, in this thesis seen as the downstream part of the supply chain from the view of the torrefaction plant
- Forwarding = Within this thesis and the bioenergy literature, a term for in-forest transportation of biomass
- CHP = Combined heat and power plant
- DH = District heating
- Comminution = Crushing or grinding of biomass into small pieces, which are often labelled as forest chips

1 Introduction

This chapter introduces the reader to the topic of the thesis. The background presents the research gap and the justification for the research. This is followed by a discussion of the problem area. From this, the purpose and the research questions are derived and presented.

1.1 Background

Energy is a source of power that is produced through networks of companies using different technologies to transform a variety of energy carriers (e.g., solid, gaseous, liquid and kinetic energy) to consumable energy entities such as electricity, heat and vehicle fuel used by industry and in households (Halldórsson and Svanberg, 2013). Together with the logistics activities involved in the procuring of feedstock and the distribution of electricity, heat and vehicle fuel, this constitutes energy supply chains, e.g., a biomass-to-energy supply chain. A transition from conventional non-renewable fossil fuel to renewable energy sources is desirable for several reasons. Firstly, conventional energy resources such as oil and coal are limited and not replenishable. Secondly, fossil fuels have a large carbon footprint causing global warming. Thirdly, a diversification of energy sources is vital for energy security and securing a long-term energy supply. Among the feasible alternatives is to increase biomass use. It has been estimated that only 2/5 of the worldwide potential is utilised, a potential which could replace 30% of the current energy use (Parikka, 2004). More recent studies have concluded that only half of the woody bioenergy potential in Europe is utilised (Alakangas et al., 2012).

Research on biomass-to-energy is extensive from a technical perspective. As shown a decade ago in two review papers, there has been plenty of research on conversion technologies for biomass-to-energy such as gasification (McKendry, 2002b) and other conversion technologies such as combustion (McKendry, 2002a). However, a transition from non-renewable energy sources to renewable energy sources is more than a technology shift in terms of type of technology used to convert energy; it is a transition in supply chains as well. For example, coal is sourced in single points (mines) and has good storage and transportation properties whereas biomass has poor transportation and storage properties and is scattered in multiple points, e.g., in small amounts over large areas resulting in covering flows. Furthermore, technical reasons are not to blame for hindering increased bioenergy utilisation; rather, economic conditions and supply chain co-ordination are among the barriers (McCormick and Kåberger, 2007). It is hence justified to address and assist in the energy transition from a supply chain perspective.

As shown in two recent reviews (Iakovou et al., 2010, Gold and Seuring, 2011), there has been a significant amount of research on biomass-to-energy supply chains over the last couple of years. Current research on biomass-to-energy logistics has to a large extent been focused on regional supply of biomass. Research methods used have been techno-economical evaluations on different biomass-to-energy supply chains and developing different optimisation and simulation models using geographical information systems (GIS) to design

supply chains. Central issues have been regional biomass supply systems for industrial use in combined heat and power plants (CHP), focusing on which logistical resources to use, network design, transport via terminal or not (Gunnarsson et al., 2004), where terminals should be located (Kanzian, 2009) and assessing the optimal size of power plants from a system perspective (Cameron et al., 2007).

1.2 Problem area

1.2.1 Barriers to increased biomass use

In order to increase the use of biomass, a number of barriers need to be overcome. Biomass has often been seen as a fuel to be used locally or regionally due to poor transportation properties such as high bulk volume, low energy density, and high moisture content. However, towns cannot always be supplied with local biomass and costly long-distance transportation is required (Möller, 2003). In transatlantic supply chains, distribution cost for pellets accounts for a significant share (about 62%) of total procurement cost (Sikkema et al., 2010). Also, transportation distances will increase even further when biomass utilisation is increased and longer transportation distances implies even higher transportation cost. Furthermore it is often noted that the lower energy density of biomass compared to fossil fuel makes transportation a relevant cost factor in biomass-to-energy supply chains (Gold and Seuring, 2011). Hence, transportation cost is a barrier in the transition to increased used of biomass and an important issue for logistics researchers.

A second barrier to overcome is the problems with biomass as a good, e.g., poor storage properties. Given that biomass is a biological product, it has some perishable properties, e.g., once forest fuel has been comminuted it should be used within one week in order to avoid substance losses that can range from 6.6-16.6 wt% during 6 months of storage (Wihersaari, 2005). Conventional pellets require covered storage in order to overcome remoistening problems. There are hence time constraints on storing that need to be taken into account when designing the supply chain. Storage of biomass has no eigen-value but is required in order to bridge the gap between supply and fluctuating demand due to weather seasons and short-term fluctuations.

A third barrier is the current energy infrastructure, which is to a large extent adapted to fossil fuel, e.g., large investments have been made in coal-fired power plants. Conventional woody pellets can only to some extent be used in pellet plants, up to a co-firing rate of about 10% due to pellet properties. The three identified barriers can be summarised as a major barrier, which can be labelled as a barrier regarding movement of energy. There is a large potential of renewable energy but it needs to be moved through space (between places), through time and through existing energy infrastructure in order to be accessible and consumable for households and industry. It is hence further justified to address the energy transition from fossil fuel to biomass from a supply chain perspective, given that movement of goods in time and place, and the design of physical networks are central themes within the research field of logistics, c.f. Hesse and Rodrigue (2004).

1.2.2 Introduction of process technology to overcome barriers

One instrument in overcoming the aforementioned barriers and increasing the use of biomass is to implement a new process technology early in the supply chain, which can improve the transportation and handling properties of biomass. These new properties can help overcome the existing barriers of movement of energy through place, time and energy infrastructure. Pre-treatment is in this thesis defined as a process that alters (enhances) the product properties of biomass. There are a number of pre-treatment processes to choose from, e.g., torrefaction, pyrolysis or steam explosion. For research funding reasons, the focal one in this thesis is torrefaction, which is a thermochemical process using heat (about 200-350˚C) to "dry" biomass. In combination with a subsequent densification process such as pelletizing, torrefied densified biomass (TDB) is attained. This has implications both for (1) higher product quality, which can be used to charge a higher price or to target new customers, and for (2) logistics properties of biomass, enabling more efficient transport and handling of biomass. Firstly, quality is improved, as torrefied biomass is a commodity that has properties resembling coal in many aspects and that has far superior efficiency to traditional biomass when co-firing with coal. This could be exploited to overcome the aforementioned barrier of existing energy infrastructure. Furthermore, quality is also enhanced, as different types of low unknown heterogeneous quality biomass can be torrefied into high known heterogeneous quality biomass. This can be utilised by customers having high demand on quality of biomass for energy production such as different types of small-scale boilers used in households. Secondly, regarding logistics, transportation and handling efficiency is improved through increased energy density of up to a factor 7 depending on what type of biomass it is compared to (forest residues, conventional pellets, etc.). Given that the process significantly improves handling and transportation properties, there is a possibility that a decentralised (located early in the supply chain) torrefaction plant could make it possible to access the biomass potential that is not economically feasible to utilise with current supply systems. Hence, a torrefaction process is both a vital part with regard to the production system, as it increases quality and value of biomass, but also an important part of the logistics system as it enhances product properties, which helps overcome the aforementioned barriers regarding movement of energy.

1.2.3 Previous research on torrefaction in a supply chain perspective

Torrefaction is often suggested as a major improvement in logistics (Richard, 2010, Sikkema et al., 2010) and some early results point to the cases when torrefaction is preferable from a logistics perspective, e.g., in comparison to conventional pellets (Bergman, 2005a, Uslu et al., 2008). However, current research on torrefaction supply chains (in this thesis defined as a biomass-to-energy supply chain containing a torrefaction process) research is sparse and has been pointed out as an important research topic; for example, identifying torrefaction scenarios and the industries that benefit most from the process (Ciolkosz and Wallace, 2011). Torrefaction offers a range of potentially beneficial logistics properties but the actual benefits depend upon how the supply chain is configured to address various elements of customer demand.

Recent review papers of torrefaction technology (Ciolkosz and Wallace, 2011, Chew and Doshi, 2011, van der Stelt et al., 2011) have shown that it is possible to use a vast number of different types of biomass for torrefaction and that torrefied biomass has several potential applications such as small scale combustion, gasification or co-firing with coal. In a supply chain perspective, there are a number of decisions to make regarding feedstock selection, supply system, torrefaction plant, distribution system, and customer demand (see Figure 1).

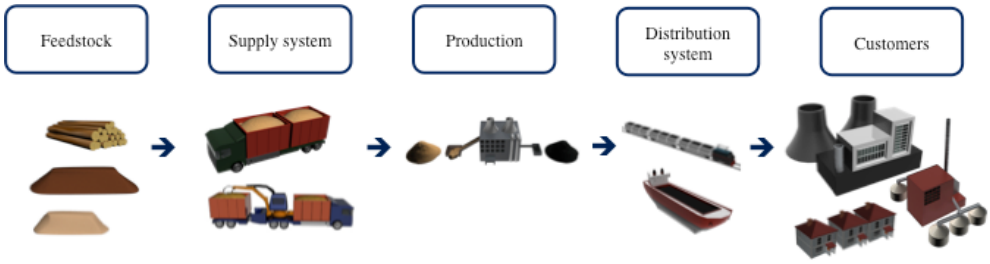

Figure 1: A torrefaction supply chain

For conventional pellet supply chains, it has been shown that understanding aspects regarding the plant such as location but also regarding up- and downstream decisions, in order to make the supply chains cost-competitive. Firstly, Smith and Junginger (2011) evaluated location as a function of feedstock, investment climate, electricity prices, market potential and logistics. It was concluded that some regions are more favourable than others, but factors such as increases in ocean freight demand quickly reduce the performance of long distance supply chains. Secondly, Wolf et al. (2006) have noted that there are diversified prices for the feedstock used for pellet production. Pellets made of cheap feedstock such as bark can only be sold to large-scale customers, as bark pellets are not suitable for use by small-scale combustion. However, pellets made from high quality feedstock, such as sawdust, can be used by both small and large customers (ibid). The procurement strategy hence has to be decided in connection with market strategy. Thus, understanding configuration within conventional pellet supply chains is important in order to achieve cost-competitive supply chains. The same logic holds for torrefaction supply chains, with the addition that torrefaction enables a number of enhanced logistics benefits, for which the supply chain implications need to bee understood, in order to make them cost-competitive. Hence, based on this discussion, a research scope for this thesis is pinpointed and justified, which is to provide the industry with logistics knowledge regarding configuration of a pre-treatment process in a supply chain perspective.

1.3 Purpose and research questions

To sum up the discussion so far, it is concluded that biomass-to-energy is one feasible environmental pathway in order to overcome the problems related to fossil fuel. Current research on biomass-to-energy has been extensive for a long time with regard to technical aspects of energy conversion, but supply chain research is important as well. There is an unutilised potential of biomass that is hard to access due to barriers regarding movement of energy through place, time

and existing energy infrastructure. One advancement to overcome these is to introduce a new process technology such as torrefaction that renders a commodity that has quality and logistics benefits. However, there is a research gap regarding how to make use of these logistical benefits and how to configure the torrefaction process into different supply chains. Understanding supply chain configuration is important in order to make torrefaction biomass-to-energy supply chains cost-competitive. Torrefaction has not yet reached full commercialisation, and in order to make a contribution to this development, this thesis will address the supply chain perspective for the torrefaction process. Hence, this leads to the purpose of this thesis:

The purpose is to understand the logistics implications of a pre-treatment process in order to propose supply chain configurations.

For clarification, two central terms are *supply chain configuration* and *torrefaction configuration*. These will be discussed further in the frame of reference and are defined as follows:

- Supply chain configuration refers to decisions regarding the physical flow of biomass in terms of how components such as nodes and links are combined into networks for the physical flow of biomass.
- Torrefaction configuration refers to decisions regarding the organisation of production as well as upstream and downstream activities seen from the perspective of the torrefaction company.

1.3.1 Research questions

In order to fulfil the purpose, three research questions have been identified. Firstly, when implementing a new process technology into a system, it is essential to understand the system components in order to configure the new process effectively and efficiently. For this thesis, this means taking a system perspective and identifying what characterises the physical flow in existing biomass-to-energy supply chains without torrefaction processes. The justification for putting so much focus on identification of characteristics is, for example, that biomass differs from many other types of goods, e.g., as a function of it being a biological product and being low-valued and handled outside, which has implications for supply chain configuration. Through identifying characteristics, a basis for further analysis regarding the logistics implications of a torrefaction process is provided. Hence, the first research question is phrased as:

RQ1: What characterises the physical flow in biomass-to-energy supply chains?

As previously argued, the new process-technology opens up new possibilities regarding customers, e.g., torrefaction of forest residues to replace coal in power plants. Previous research has shown that it is possible to use a vast number of different types of biomass for torrefaction and TDB has several potential applications. This renders a number of possible supply chain configurations and for these, torrefaction offers a range of potential logistics benefits, e.g., enabling overcoming the aforementioned barriers regarding movement of energy through time, space and infrastructure. It is hence justified to present an approach on how torrefaction can be configured in different supply chains. This is addressed through the second research question:

RQ2: What are the implications of a pre-treatment process on supply chain configuration?

The aim is to answer the second research question through developing a framework, which entails propositions on supply chain configurations. These propositions can in turn be further evaluated using quantitative approaches, e.g., techno-economic modelling. Furthermore, in Sweden, there is currently some areas of large unutilised potential of biomass, see light grey areas in left-hand side of Figure 2. Hence, an important task is to assess the structure of the supply chain, which e.g., can be configured according to the structure seen in the right-hand side of Figure 2, and in particular identify how different parameters affect the cost of the supply chain.

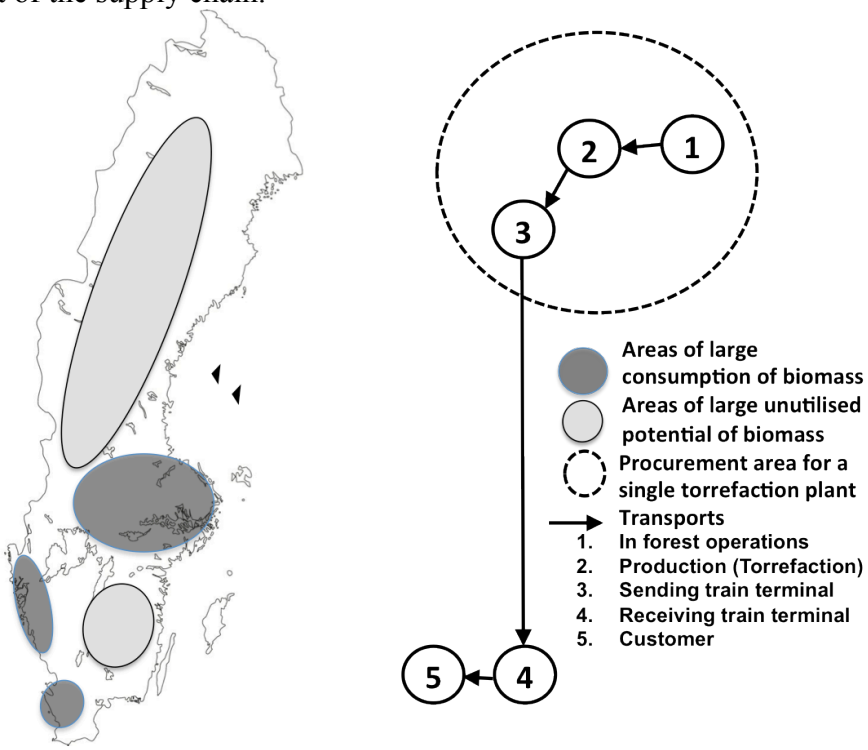

Figure 2: Areas of large unutilised potential of biomass and areas of large consumption, left-hand side, and a possible supply chain (not according to scale), right-hand side

Supply chain modelling has a long research history and factors that are often targeted by researchers are: capacity, inventory, procurement, routing, production and transportation modes (Melo et al., 2009). Within biomass-to-energy research, focus is often put on size of CHP's, see e.g., (Kumar et al., 2003) and (Cameron et al., 2007) as well as size of conventional pellet plants, see e.g., (Nilsson et al., 2011) and Sultana et al. (2010). As shown in these papers, it is important to have a systems perspective, as both logistics and production economy are affected by plant size and hence affect supply chain cost. The logistical constraint is derived from the fact that biomass is a scattered resource, and the larger a plant is, the longer the average transportation distance and hence increased haulage costs (Cundiff et al., 2009, Jack, 2009). However,

when the size of a bioenergy plant increases, energy production reaps advantages from economies of scale of the production processes and hence there is a trade off between economies of scale of production and diseconomies of scale (transportation distance) of procuring biomass. This argument has two implications for this thesis. First of all, it justifies the importance of identifying how different parameters influence supply chain performance in terms of cost. Secondly, it justifies using a systems perspective as a methodological approach for modelling the torrefaction supply chain.

Hence, in order for the torrefaction supply chain to be cost competitive it is essential to take a systems perspective to understand how different torrefaction configurations affect the performance of the supply chain, e.g., in terms of cost. There are many decisions that could potentially influence supply chain cost such as decisions on logistics equipment or production strategy in terms of which quality of the product to produce. The third research question is hence phrased as:

RQ3: How does torrefaction configuration relate to supply chain performance?

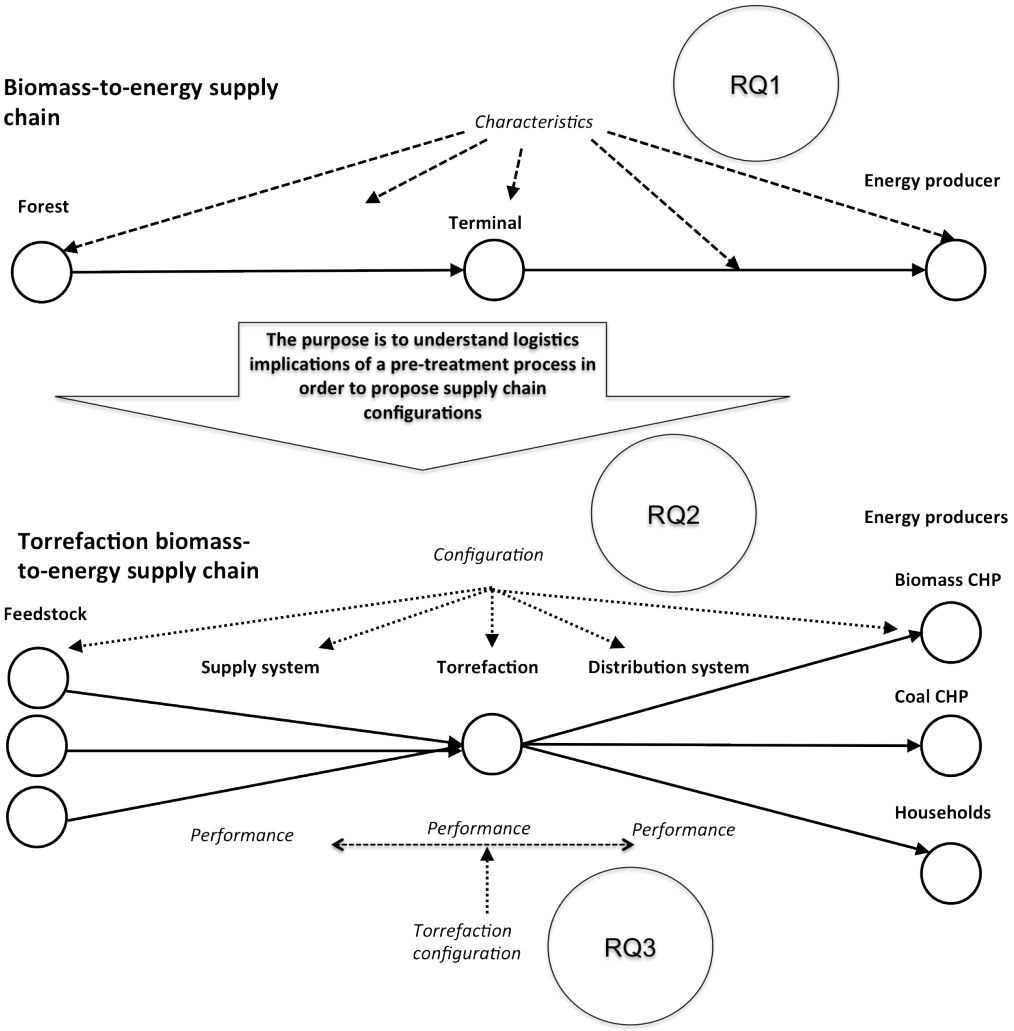

Figure 3: Purpose and research questions

To sum up, the relations between the research questions and the purpose can be seen in Figure 3.

1.4 Scope and delimitations

One of the ultimate goals of technology implementation is to, in quantitative terms, answer when the benefit of the technology outweighs the cost, e.g., in this case: "Under what circumstances is it preferable with a torrefaction process?" However, this is beyond the scope of this thesis due to the current research state of torrefaction and the current lack of reliable accurate quantitative data. First, there are gaps regarding cost of logistics in terms of handling and storage. For example, it has been shown that TDB requires less energy during grinding operations than forest chips (Repellin et al., 2010). However this ought to imply that TDB is more sensitive to handling operations in the supply chains, resulting in more handling loses, but this has not been quantified yet. Secondly, with regard to energy conversion, the efficiency of TDB compared to other unrefined biomass and conventional pellets is not known. Hence, focusing on comparison of torrefaction supply chains to unrefined forest fuel or pellets is at present not possible due to a lack of reliable quantitative data.

Thus, supply chain focus is in this thesis not on comparison, but rather on providing support for future configuration of torrefaction supply chains, assuming that there will be torrefaction supply chains. An obvious question is then: Is it valid to base the research on the assumption that there will be torrefaction supply chains? The answer is "yes", given that it is likely that there will be torrefaction supply chains in the future for two reasons. First of all, as earlier stated, Bergman (2005b) and Uslu et al. (2008) showed in two early works that there are cases when torrefaction is preferable over conventional pellets. These studies were performed in the early phase of torrefaction research and had to make some assumptions given that, for example, no large-scale tests on torrefaction had been performed. Still, even though data is little bit uncertain, they do point in a certain direction when it comes to the economic viability of torrefaction supply chains. Secondly, simple logic implies that there ought to be supply chains where torrefaction is beneficial. As earlier argued, the distribution cost of pellets accounts for a significant share of the total procurement cost in trans-Atlantic supply chains, and ocean transportation alone accounts for 44%. Torrefaction could potentially enable doubled transportation efficiency, thus cutting the costs in half, which would be a significant save. In comparison, the handling losses for conventional pellets in ocean transport are about 2% (Sikkema et al., 2010) and it is not likely that the torrefaction handling losses of TDB will be that much larger that they would outweigh the gains in reduced transportation cost. Furthermore, the cost of energy conversion of TDB compared to conventional pellets is likely to be rather similar. Hence, it is valid to assume that there will be cases when torrefaction benefits outweigh the cost of the process, and that there will be torrefaction supply chains in the future. However, when reliable quantitative data is available, future research will need to address under which circumstances the torrefaction process is beneficial.

2 Research design

This chapter presents the research design used in this thesis. It starts by discussing research design in general, and then takes a plunge into five central elements of research design and how they were approached in this thesis.

2.1 A model of research design

The research design can be defined as a logical plan for how to get to the conclusions of the research questions posed (Yin, 1994) or *"a framework for the collection and analysis of data"* (Bryman and Bell, 2007). The model used to describe the research design in this thesis is "*an interactive model of research design*" (see Figure 4), adapted from Maxwell (2005).

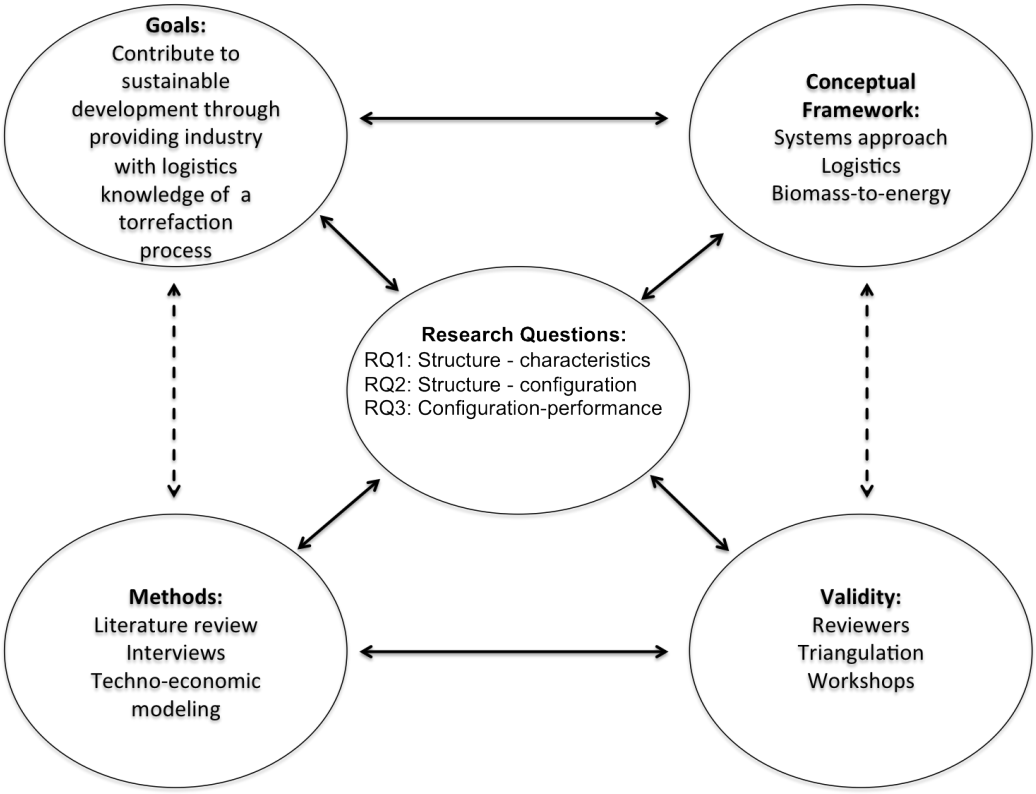

Figure 4: A model of research design, adapted from Maxwell (2005)

The elements of the model are: (1) goals of the research, (2) the conceptual framework used, (3) research questions, (4) methods, and (5) validity. In the phrasing, "interactive" lays out the necessity to go back and forth between the different components and assess the implications and threats for one another. The components must work together in order to function efficiently and successfully (ibid). Other authors provide similar arguments, that there are a number of factors that affect how research is performed. E.g., Bryman and Bell (2007) argue for the following influences on business research: theory, values, practical considerations, epistemology and ontology. Similarly, Yin (2009) argues for the following factors: the type of research question posed, the extent of control an investigator has over actual behavioural events and the degree of

focus on contemporary as opposed to historical events. It is hence justified to discuss how different elements of research design are related, which in this thesis will be done using the model provided by Maxwell (2005), in which the bold text represents the original model and the rest is the view of- and choices made by the author, which will be justified in the coming sections (see Figure 4).

2.2 Goals

Goals can be defined broadly as motives, desires and purposes – reasons for doing research (Maxwell, 2005). Goals are important as they guide other research decisions and help justify why the study is worth doing. Goals can be distinguished based on whether they are personal, practical or intellectual.

Personal goals are important as they serve as motivation and affect choice of research approach (Maxwell, 2005). The personal goals behind this research are twofold. First of all, research as a way of working is perceived as an intellectually stimulating and meaningful way of spending daily time by trying to gain new knowledge to make a contribution to society. Secondly, doing research in the specific area, the intersection between logistics and energy is perceived as meaningful as it assists in the transition from fossil to renewable fuels, which contributes to sustainable development.

The practical goals in this thesis are narrower than the personal goals. Given that it was pre-specified to do research on torrefaction due to funding reasons, and that the torrefaction process has not reached full commercialisation yet, the current practical goal of this research is hence to provide the industry with logistics knowledge that assists in configuring torrefaction in a supply chain perspective.

Whereas practical goals are important for justifying the research and focus on accomplishing something, intellectual goals focus on understanding and are fruitful for phrasing research questions (Maxwell, 2005). The intellectual goal behind this research is to contribute to knowledge regarding how process-technology altering product properties can be used to increase the efficiency in a flow of goods, in particular within the biomass-to-energy context. There is hence a good fit between the personal, practical and intellectual goals of this thesis.

2.3 Conceptual framework

The conceptual framework is a key part of the design going beyond a mere literature review, consisting of the system of concepts, assumptions, expectations, beliefs, and theories that support and inform the research (Maxwell, 2005). The literature review of the research fields and how it is related to the research questions is presented in Chapter 3. The research strategy is shaped by assumptions made on ontology, epistemology, the personal values and beliefs of the researcher. The epistemological debate concerns what can be regarded as acceptable knowledge within a discipline, and whether social sciences can be studied according to the same principles, procedures and ethos as the natural sciences (Bryman and Bell, 2007). The ontological debate is

concerned with the nature of knowledge; in other words, the researcher's view of the world from an objective or subjective perspective (ibid). The author's view of the world is that reality definitely exists, e.g., on a basic level the world is made up of atoms and molecules and everything could hypothetically be measured. On a more specific level the view is that there is "a best" configuration for biomass-to-energy supply chains in a specific context if all variables are known. However, an optimal configuration cannot be identified given that the world cannot be fully understood due to complexity and comprehensiveness, only proposed or evaluated differently based on the author's knowledge of the world and the research field in particular. The best fit with textbox definitions on ontology and epistemology is the post-positivist view (c.f. Guba (1990)). Within this, the view on ontology is critical realist, where "*reality exists but can never be fully apprehended. It is driven by natural laws that can only be incompletely understood."* The epistemological stance is modified objectivist where "*objectivity remains a regulatory ideal, but it can only be approximated, with special emphasis placed on external guardians such as the critical tradition and the critical community" (ibid).*

The research strategy is influenced by the researchers' assumptions of scientific paradigm, which in this thesis is the systems approach. The essence is that the whole of the system is not equal to the sum of its parts (Arbnor and Bjerke, 1997). The justification of the paradigm can be exemplified by the interaction between the torrefaction process and the supply system for feedstock, the input to the process. The process itself reaps advantages from economies of scale. However, given that biomass is a scattered resource, and the larger a plant is built, the longer the average transportation distance becomes, there is a diseconomy of scale of supplying large plants. There is hence a trade-off between the efficiency of the process and the efficiency of input to the process, which justifies addressing the process and hence research through a systems approach. This implies that when addressing the performance of the process, e.g., in terms of cost, this should be done through a systems approach.

A key assumption in this thesis is that supply chain configuration for torrefaction can be proposed based on related research fields such as unrefined forest fuel, pellets and coal logistics. The justification for using this body of knowledge lies in the fact that the torrefaction supply chain will share characteristics in terms of point of departure (same type of feedstock) and point of consumption (same/similar type of energy production). The configuration of the supply chain will not be the same given that torrefied biomass has superior transportation and handling properties, but it is likely to share attributes, e.g., subject to the same issues in transportation of goods. Hence, attributes are likely to be the same, but the magnitude of attributes might differ.

2.4 Research questions

In the interactive model of research design (Maxwell, 2005), the research questions are central as they directly link all the other components, e.g., in terms of relationship to methods and validity. Research questions should be framed to point toward the information and understanding that will help accomplish the practical goals of the researcher (ibid). Similarly, Flick (2009) argues that decisions about research questions often depend on the practical interests of the

researcher. They are the starting point and determinant of the research design and help the focus of the study and give guidance on how to conduct the study (Maxwell, 2005). The formulation of research questions needs to be clear, as the research questions act as a control mechanism ensuring the focus the research, and in the end, essentially determine the success of qualitative research (Flick, 2009). With the methodological discussion so far in mind, it is time to restate and discuss the implications of the formulation of the research questions presented in chapter one:

RQ1: What characterises the physical flow in biomass-to-energy supply chains?

RQ2: What are the implications of a pre-treatment process on supply chain configuration?

RQ3: How does torrefaction configuration relate to supply chain performance?

The first research question does not meet the specification of directly fulfilling any of the goals presented. However, it is necessary to address this question as this provides knowledge, which is part of the foundation of answering the second research question and addressing the overall purpose in this thesis. The second and the third research questions correspond well to meeting the practical goal of this thesis, which is to provide the industry with knowledge that will assist them in implementing torrefaction plants in biomass-to-energy supply chains. This is also in line with the personal goals, as answering these research questions provides knowledge that is a brickstone in contributing to sustainable development. Hence, the questions correspond well to meeting the goals of the researcher.

There is also a relation between phrasing of research questions and method selection. RQ1 is phrased with the word *characterises*, which refers to identification, and which implies that literature review in combination with interviews could be suitable methods. Given the assumption on systems approach as research paradigm, it is necessary to do interviews with different actors along the supply chain. Similarly, RQ2 implies the same method, but interviews are excluded as pre-treatment processes are not yet used on an industrial scale and performing interviews might not result in useful knowledge, as it might be hard for interviewees to have an opinion about a non-existent process. From the phrasing of RQ3 it can be concluded that modelling is suitable, given that the words “how” and “affect” are used, which aims at capturing a relationship. In addition, as a systems approach has been argued for, it is required to include the entire supply chain in the model. Furthermore, the selection of methods is further justified below with respect to each paper.

2.5 Method

Decisions about method are dependent on the specific context and the research issue as well as the other components of the research design (Maxwell, 2005). Similarly, Marshall and Rossman (2006) argue that it is important to match data collection method with the purpose of a study. This section is devoted to discussing the selection of methods, in terms of why they are suitable, how they match the research questions, and important aspects of the design of the studies within this thesis. This section is structured around the selection of method

within each paper and finishes by giving an overview of the entire research process behind this thesis. However, two aspects are essential to address prior to method selection. Firstly, an important decision is on how research can be approached in terms of inductive/deductive/abductive approaches. Secondly, given that both qualitative and quantitative methods have been used in this thesis, a short discussion of mixed-methods is provided.

Traditionally, a major distinction in research is often whether an inductive or deductive approach is taken. A deductive theory is generated through developing a hypothesis based on what is previously known in a particular domain, which is then empirically scrutinised (Bryman and Bell, 2007). An inductive approach starts with an empirical observation and then tries to generate theory (ibid). A third more recently conceptualised approach is the abductive research approach (Kovács and Spens, 2005, Dubois and Gadde, 2002). With respect to this discussion, the research process in this thesis is visualised in Figure 5.

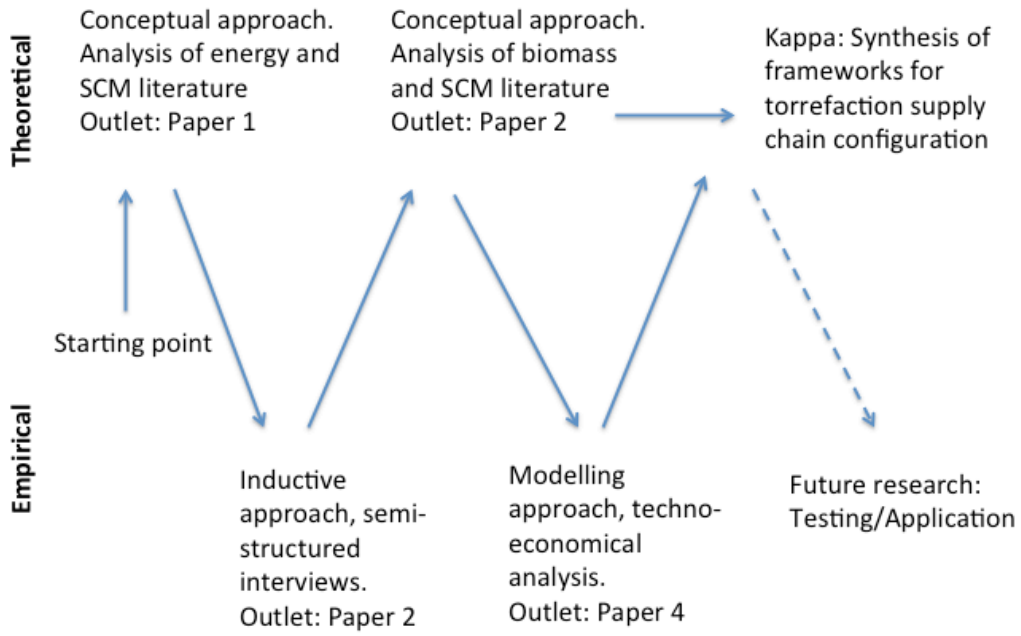

Figure 5: The overall research process

A major distinction in research is whether research is qualitative or quantitative. In this thesis, both methods are combined. Bryman and Bell (2007) state that there is a debate regarding mixed-methods, and that it is argued to be impossible to combine the research methods due to epistemological commitments and that qualitative and quantitative research are separate paradigms. However, these arguments were scrutinised and it is argued to be possible to combine the methods, e.g., it is argued that mixed-methods can be used for triangulation, facilitation or complementation. Similarly, Greene et al. (1989) identify triangulation, complementary, development, initiation and expansion as purposes for mixed-methods. In this thesis, mixed-methods has been used to answer the research questions. RQ1 and RQ2 were addressed by qualitative methods and RQ3 was addressed using a quantitative method. The justification behind this can be seen as complementary and development. Firstly, with regard to complementary, the conceptual study addressing RQ2 entailed feasible supply

chains, of which one was evaluated further using techno-economic modelling. Secondly, with regard to complementation, the papers answering RQ2 and RQ3 resulted in two bodies of knowledge at different abstraction levels, which helps address the purpose of the thesis.

Below follows a short summary of the papers with regard to how and why each research approach was taken, and how data was collected and analysed. The full methodological approach can be read within each paper. A summary of the papers can be seen in Table 1

Table 1: A summary of the research in each paper

Paper	Approach	Data collection	Data analysis	Contribution
1	Explorative	Literature	Categorisation of literature findings according to major themes of SCM	RQ1
2	Explorative/ Descriptive	Literature and interviews	Categorisation of literature and empirical data according to different stages of the supply chain. Sub-categorisation according to efficiency factors and external factors	RQ1
3	Explorative	Literature	Categorisation of literature findings according to attributes of different stages of the supply chain	RQ2
4	Explorative	Literature as a foundation for model development. Literature and interviews for data collection to model	Analysis of numerical results according to different (1) system parts, different and (2) different activities. Sensitivity analysis on central parameters	RQ3

Paper I

The paper was explorative, taking a conceptual approach. The scope was the entire energy supply chain, ranging from raw material, via energy producers, to energy consumers, which is in line with the assumption on systems approach as research paradigm. In order to provide arguments for the discussion, a structured literature review of a number of SCM Journals (see paper I for a full list) was performed. Keywords included “energy” in combination with “fuel”, “oil”, “gas”, “electricity” and “renewable”. However, not much was found and an additional review of papers from energy-related journals, and in particular bioenergy journals was performed. This literature was analysed and categorised with respect to major themes of SCM: activities, benefits and components.

Based on this, three trajectories for energy supply chain management were proposed. The paper partly helps in answering RQ1, but it is also a part of the foundation and justification for the thesis.

Paper II

The study was explorative and descriptive, aiming at identifying the view of actors working within forest fuel logistics. Semi-structured inductive interviews was chosen as a suitable research method as it allows interviewees to discuss the issues brought up, but at the same time introduce new issues. This is in line with the view of Bryman and Bell (2007) who argue that a strength of the qualitative interview lies in capturing the view of interviewees by allowing for "going off", giving an insight to what the interviewee sees as relevant and important. The method selection is hence in line with the research question in the paper, phrased using the word *"which"*, aiming at identifying and describing factors influencing supply chain configuration. The assumption of systems approach is in this paper manifested in the sense that different actors along the supply chain were interviewed, ranging from companies working with producing (supplying) forest fuel, via handling and transportation companies, to energy producers. These were sampled to represent different conditions, e.g., as a function of regional differences in climate and infrastructure, in order to possibly obtain a diversity of answers. Companies producing forest fuel differed mainly on where they were located. Companies performing transportation and handling differed on where they operated, the scope of their business (only biomass-for-energy or other types of goods as well) and the scope of the number of activities they were involved in, e.g., merely transportation, or handling and storing as well. Companies producing energy differed on location, number of power plants used to produce energy, and type of energy produced (through district heating or combined heat and power plants). Due to proprietary reasons, the companies were ensured anonymity. A general criteria for the selection of interviewees is that the interviewee should have the knowledge and experience to answer the questions (Flick, 2009). The interviewees targeted were logistics managers, as these are the ones responsible for the decisions made within the supply chain. In total, 5 managers of forest fuel companies, 5 managers of energy companies, and 5 managers of logistics companies were interviewed. The data was collected over the telephone, lasted for 30-60 minutes and was transcribed after the interviews.

The interview guide was based on two foundations. The first included decisions that are often addressed by researchers within supply chain modelling: capacity, inventory, procurement, routing and transportation modes (Melo et al., 2009). In order to avoid being too narrow, the questions were furthermore based on a general aim of logistics, the 7R, which has been defined as receiving the right goods or services in the right quantity, right condition, right time, right place, to the right customer, at the right cost (Lumsden, 2006). These decisions and aims were then addressed in different stages in the supply chain, for example, how does quality aspects influence decisions on vehicle selection within transportation, or which factors influence the location of a terminal. See appendix A for the interview guide.

Data from the literature and interviews was analysed according to stages in the supply chain and then categorised into different groups: external factors and efficiency factors. External factors comprise those that need to be taken into account, which are often constraints of supply chain configuration. Efficiency factors comprise contextual aspects of the biomass-to-energy supply chain, which basically describes factors that influence efficiency within a node, link or the overall network configuration. For a further description of methodology see paper II. The paper mainly contributes to answering RQ1.

Paper III
The paper took an explorative conceptual approach, aiming at developing a framework for torrefaction configuration. In order to provide support for how a framework can be developed, a review of SCM literature, with a focus on key terms such as structure, configuration and design was performed. Secondly, with regard to content of the framework, literature concerned with forest fuel, pellets and coal logistics was reviewed. The systems approach permeated this paper as well, as literature was analysed and categorised according to different levels in the supply chain, ranging from feedstock to customer demand. Based on this, a conceptual framework was proposed, with a set of determinants that can be used for profile analysis. A more detailed description of the method can be read in the paper. The paper mainly contributes to answering RQ2.

Paper IV
In the fourth paper, techno-economic modelling was chosen as a suitable research method, as it allows for identification and quantification of relations of components within a system. Hence, this approach is loyal to the assumption of systems approach as paradigm. The system in the modelled supply chain ranges from source of feedstock to the gate of a CHP. The supply chain was modelled to be representative in a Swedish perspective based on where there are large unitised potential of forest residues, and where the potential customers of TDB can be located. However, transportation distances were addressed in a sensitivity analysis.

In order to construct the Microsoft Excel based techno-economic model, a literature review was performed. This consists of reviewing of how papers of related supply chains were modelled and which activities could or should be included and evaluated in the model, and which parameters to address in a sensitivity analysis. Furthermore, in order to attain data to the techno-economic model, numerical data was drawn from the literature and from interviews with technology suppliers. In addition, eight visits to different existing conventional pellet plants were performed during 2012, where interviews were conducted as a data collection method, in particular for estimations on personnel requirements. Finally, a number of secondary sources were used for to attain additional numerical data, see paper IV for details on data collection.

The paper was mainly exploratory, where the results of the model were analysed with respect to different system parts (supply system, production, distribution system) but also with respect to different activities within the system parts. Furthermore, a sensitivity analysis was performed to address the importance of a number of central variables. This is based on different decisions that can be

made and uncertainties within the data. Furthermore, the variance of some variables, represent settings in other supply chains, e.g. due to regional variances in amount of available biomass and moisture content. The main contribution of the paper is with respect to RQ3. For a full description of model development and data analysis, see paper 4.

2.6 Validity

Validity can be defined as the "correctness or creditability of a description, conclusion, explanation, interpretation, or other sort of account" (Maxwell, 2005). Common criteria of quality are often argued as internal validity, external validity, reliability and construct validity (Ellram, 1996, Mentzer and Kahn, 1995, Yin, 1994). Furthermore, Guba (1990) argues that these criteria are appropriate for positivism or post-positivism. The latter has previously been argued as the view of the author of this thesis and the four proposed validity criteria are hence suitable as means for addressing validity in this thesis. Internal validity is mainly for explanatory case studies and is hence not addressed here.

Construct validity refers to if what was intended to be measured was actually measured (Karlsson, 2009). Construct validity is mainly an issue for the interview study and for the techno-economic modelling. In order to ensure validity of the interview guide, it was evaluated by a researcher working within the department of the author, but also by an external researcher working specifically within forestry industry research. In addition, interviewees were asked if they perceived an important aspect of the interview guide was missing. The interviews were recorded and transcribed shortly after the interviews. When there were un-clarities the interviewees were approached with follow up questions in order to ensure that issues were correctly understood.

For the techno-economic modelling, construct validity was addressed both with regards to the overall system design, but also on a detailed level on the components in the model. The primary technique deployed was triangulation, which can be done as a means to ensure quality of data. On a component level, raw data was when possible double-checked with two or more sources, both literature and values attained from industrial actors. Furthermore, the calculated results were compared to results from similar studies in order to evaluate the feasibility of the results. The issue of overall system design of the supply chain modelled has been discussed with several industrial actors, in meetings, and on the telephone and during workshops. System design and preliminary results have also been defended and discussed during a seminar with industrial actors.

External validity refers to whether the results are valid in a similar setting outside the studied system (Karlsson, 2009). The purpose of the interview study was to identify factors affecting supply chain configuration of biomass to-energy supply chains. Given that supply chains of bioenergy differ significantly, it is likely that some factors are important in some cases and not in others. Hence, it was not aimed at, in detail, exploring factors that are important in all cases, but rather identifying factors that could be important in other cases as well, and that serves as a starting point for configuration of a supply chain. Hence, the purpose was not to reach statistical generalisation, but rather analytical generalisation. Similarly, the same logic holds for the techno-economic case as well. Even

though the research questions were phrased using “how” and quantifications were made for the specific case, the author is aware that cost will not be the same in other cases. However, it is assumed that the identified parameters within this case serve as a good starting point for configuration/evaluation of torrefaction configuration in other cases as well. Furthermore, the sensitivity analysis pointed towards results that can also be used in other cases.

Reliability refers to what extent a study can be repeated with the same results (Voss et al., 2002). Reliability for the interview study is assured by the documentation of the interview guide and the interviews. Reliability for the techno-economic modelling is assured, as the model used is well documented and all assumptions are clearly stated.

Validity of the papers has also been achieved through different reviewers’ critical comments. Papers I, III and IV have gone through a double blind review process and are published. Furthermore, paper III has also been read and commented upon by two experts on technical aspects regarding torrefaction and by one SCM-researcher. Paper II has been presented and defended in different versions at two international research conferences.

3 Frame of Reference

The frame of reference is a part of the conceptual framework and consists of a literature review. The purpose of the frame of reference is to provide a foundation for the research and to position the research to relevant theories, concepts and the current body of knowledge within the research field.

3.1 Approach

This chapter starts by identifying the paramount research fields, supply chain management (SCM) and biomass-to-energy, which this thesis will use as a foundation for the research, but also make a contribution to. The research scope is then narrowed down from SCM to (1) the physical flow in supply chains and (2) the use of technology in supply chains. That is complemented by a review of papers addressing supply chain design. Finally, the current body of knowledge within biomass-to-energy logistics research is presented, which provides the contextual knowledge required for addressing the purpose of the thesis. A summary of how the chapters relate to each other can be seen in Figure 6.

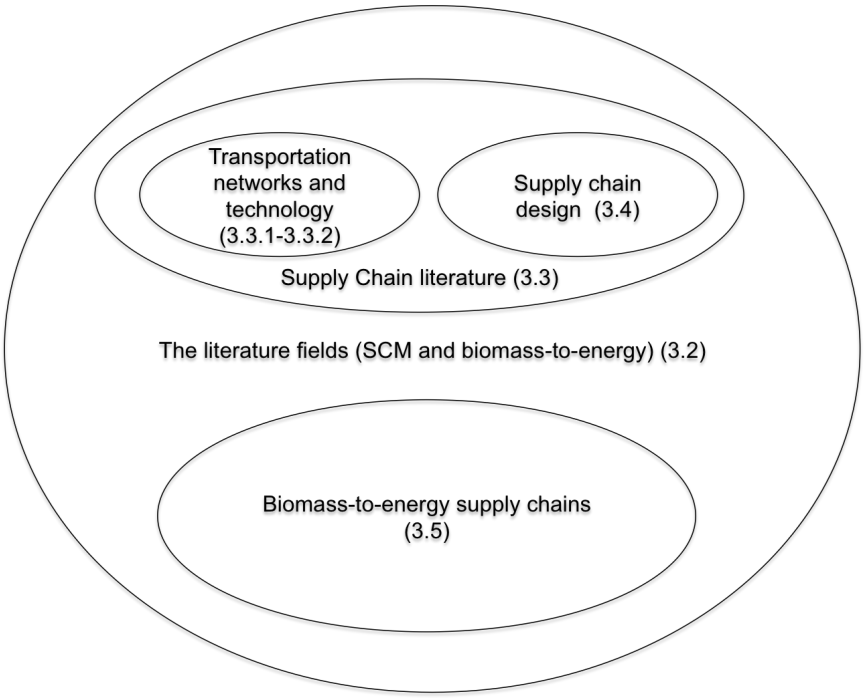

Figure 6: The relation between the literature parts

3.1.1 Links to research questions

As argued in the research design chapter, there should be strong links between the components of the research design. Below follow some of the links between the frame of reference, which is a part of the conceptual framework, and how it is used to address the research questions (see Figure 7). Out of the five sections in this frame of reference, it is primarily within the last three that the strongest links can be observed. Chapter 3.4 was used as a foundation for how to create a framework for torrefaction configuration, which was used to address RQ2. Chapter 3.3.1 was used for some aspects within the framework for torrefaction configuration. Chapter 3.3.2. served as input for the framework development in

paper two, answering RQ1. Chapter 3.5 had several important purposes: Firstly, it was used to establish the context for the development of the torrefaction configuration framework. Secondly, it was used as a complement to the interviews used to address RQ1. Thirdly, it was used as a basis for construction of the techno-economic system model used to RQ3.

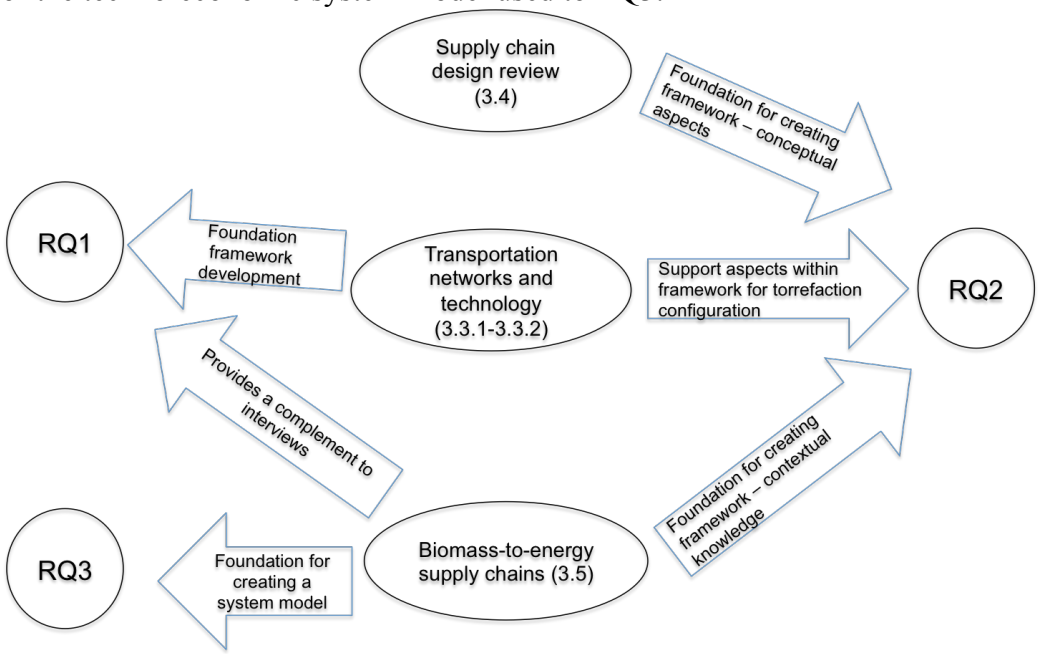

Figure 7: Relationship between research questions and the frame of reference

3.2 The research fields

The literature relevant for addressing the purpose and answering the research questions of this thesis can be divided into two parts. The first is the bioenergy literature focusing on objects (biomass and energy) and the second is the logistics and supply chain literature focusing on perspective (a supply chain perspective). Furthermore, the two bodies of literature differ on research approach, type of outcome of papers, journal type and focus (see Table 2). The biomass-to-energy literature contains papers of different research character, from pure technical papers of chemical conversion of biomass to research dealing with technological development or different types of supply chain analysis. The supply chain papers mostly use simulation, optimisation or techno-economic modelling to evaluate biomass-to-energy supply chains. The purpose of the papers is to develop mathematical models, applied to evaluate different supply chain configurations in specific geographical regions. The outcome is often the model itself, but also numerical results, e.g., the cost of producing energy from biomass or how the supply chain should be configured, e.g., location of terminals in a specific region. Hence, the useful parts for this thesis are descriptions of what are important design issues within biomass-to-energy supply chains, e.g., terminal configuration (location, size) and also some numerical results, e.g., cost of different transport modes.

In order to complement the bioenergy literature, SCM and logistics journals were reviewed. Common for papers published in these journals is research approach, e.g., taking the SCM or logistics perspective on various types of goods, but very seldom on the biomass-to-energy supply chains. The major

benefit from including this body of knowledge is theories on: (1) how to approach the matter of supply chain design, (2) what relevant aspects and principles within supply chain design are, and (3) identification of important logistics concepts. Hence, the two bodies of knowledge complement each other well regarding how to configure a pre-treatment process such as torrefaction in a supply chain perspective.

Table 2: Differences between the research fields

	Biomass-to-energy	**Logistics and supply chain management**
Journals	*"Biomass and Bioenergy", "Biofuels, Bioproducts and Biorefining", "Bioresource Technology" and "Energy"*	*"Supply chain management: An international journal", "International Journal of physical distribution and logistics management", "European journal of Operational research"*
Journal focus/Unit of analysis	Object (biomass and energy), and transformation of object	Research approach/perspective (supply chain perspective)
Research approach	Operations management, techno-economic analysis	Vast types of different case studies (from cost to pure conceptual), surveys and interviews
Research outcome	Numerical results, suggestions on specific configurations, mathematical models	Theories, concepts

3.3 Supply chain literature

In broad terms, one of the two research fields that this thesis belongs to is the research field of SCM.

Supply chain management has been defined as follows (CSCMP, 2010):
"Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies."

From this definition it is rather obvious that SCM is a comprehensive research area and the scope of this thesis has to be narrowed down further. The term "logistics" or "logistics management" can be argued as a sub-domain to SCM and has been defined as follows:

Logistics management has been defined as follows (CSCMP, 2010):
"Logistics management is that part of supply chain management that plans, implements, and controls the efficient, effective forward and reverses flow and

storage of goods, services and related information between the point of origin and the point of consumption in order to meet customers' requirements."

Hesse and Rodrigue (2004) argued that the major activities of logistics can be described by two major functions, which are physical distribution and materials management. Physical distribution comprises a range of activities for the movement of goods from point of production to final point of sale. Materials management relates to the manufacturing activities along a supply chain and comprises both manufacturing but also marketing activities. Hence, given the purpose of the thesis, this is a relevant research domain, but is still rather broad. As described in the introduction, the scope of the thesis is the physical flow of biomass, and how process technology altering product properties can be used in different supply chain configurations. Hence, it is relevant to focus on transportation networks but also on process-technology in a supply chain perspective.

3.3.1 Transportation networks

Transportation networks can be defined in terms of links and nodes (Lumsden, 2006) (see Figure 8). A node is a geographical position, which could be a source of goods, or a point for storage, processing or transhipment of goods. Nodes are connected through links, which are served by vehicles and vessels using infrastructure to transfer goods. Links and nodes can be arranged into different network types, e.g., Woxenius (2007) suggested six distinct theoretical designs of transportation networks: direct link, corridor, hub-and-spoke, connected hubs, static routes and dynamic routes.

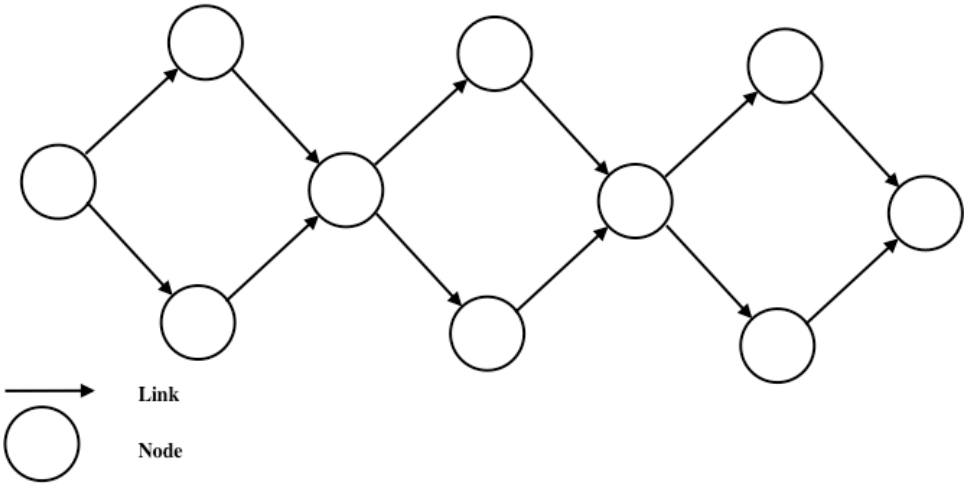

Figure 8: A model of a transportation network, adapted from Lumsden (2006)

Planning of transportation networks is crucial for supply chain efficiency. Planning is carried out at strategic, tactical and operational levels (Jonsson, 2008). Strategic planning involves decision-making at long horizons; e.g., network structure consisting of determining where to locate nodes, deciding what traffic modes should be used to link nodes and capacities of links and nodes. Decisions on tactical and operational levels are made at shorter horizons and include consolidation of deliveries, selection of distribution paths between terminals or directly between firms, planning aggregated transport quantities and

frequencies on these paths, route planning within traffic areas, vehicle loading, vehicle scheduling and tracking and tracing goods in deliveries (ibid).

Vehicles used in transportation networks can often benefit from economies of scale. For bulk shipping, Stopford (2009) defined the following principles of handling and transportation: (1) use big ships to gain economies of scale, (2) reduce handling, (3) improve handling and (4) minimise stock amounts in the system (Stopford, 2009) .

3.3.2 Technology in a supply chain context

Technology can be used in different ways in supply chains. Hesse and Rodrigue (2004) describe the benefit of technology as *"flexible order and supply behaviour is actually made possible by new technologies, primarily through the real-time exchange of information"*. Whereas the last two decades have focused on how technology can be applied to control flows of products, the focus in this thesis is how process-technology should be used to alter the product in order to achieve efficient flows. Hence, focus is not on information technology used to manage supply chains, but rather on altering product properties in supply chains. It is of course possible to combine process technology and information technology, but that is beyond the scope of this thesis.

The focal technology in this thesis is, for funding reasons, torrefaction. It is often labelled as a pre-treatment process, which is due to the fact that it is used to alter product properties of biomass before conversion into heat, energy or vehicle fuel. It is a thermal pre-treatment process in which the biomass material is subjected to a temperature in the range of about 250-350˚C for 2 to 60 minutes. Within the scientific literature, it is often referred to as "torrefaction plants", which can be misinterpreted, as torrefaction is not the only process within the plant; see Figure 9 for a schematic description of a torrefaction plant.

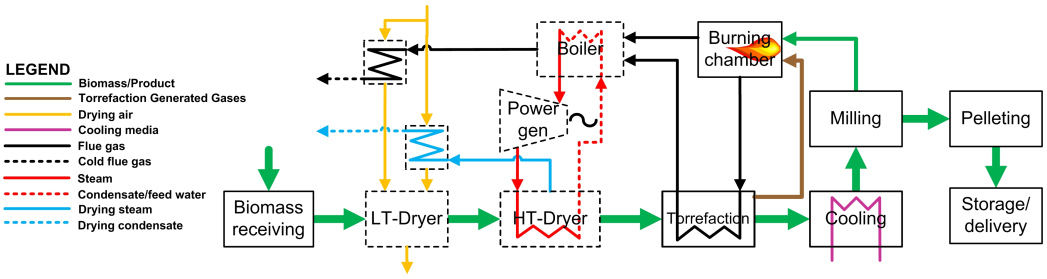

Figure 9: A schematic model of a torrefaction plant

Compared to unrefined forest fuel, TDB has superior properties. Besides increasing the transportation, handling and storage efficiency, the enhanced characteristics add value to the product by enabling co-firing with coal, rendering a superior fuel for combustion (Ciolkosz and Wallace, 2011) as well as for gasification and subsequent liquid fuels production. Torrefied pellets have good storage possibilities due to their hydrophobic properties and much less or no storage loss due to biological breakdown (Bergman, 2005a). Given that torrefied biomass has superior transportation properties compared to non-refined biomass, there is a significant potential to increase the transportation efficiency in the supply chain. In comparison to comminuted forest residues, which are

bulky and have a low energy density (about 3 to 5 GJ/m^3 on wet basis), and traditional pellets (8 to 12 GJ/m^3, >10,1 GJ/m^3 according to Swedish standard SS187120, Class 1 pellets), torrefied pellets have excellent transportation properties due to the significantly higher energy density (about 14 to 18 GJ/m^3) (Uslu et al., 2008).

Besides better transport and storage properties, there are a number of other potential benefits of torrefied biomass compared to unrefined forest fuel, such as less energy required for grinding and being easier to feed at power plants. To summarise the torrefaction process, it can be clearly seen that torrefaction is both an important production process, as it adds value to the end-user of the product, but is also a key process in enabling supply chain efficiency through rendering logistical benefits, e.g., increased transportation properties. In order to describe how these benefits can be used in a supply chain perspective, a number of relevant logistics concepts that can be used to address configuration of the process are presented below.

Given that the torrefaction plant is a physical place where transformation and storing takes place, it is useful to view the plant as a node in a supply chain, as this allows for comparison with some additional logistics concepts regarding nodes, terminals, and distribution systems, utilities and gaps. The function of the storage at the torrefaction plant can to some extent be compared to the function of a terminal for which Hultén (1997) stated that nodes are used to bridge gaps between means of transport within the physical flow of products in terms of frequency, capacity and time (see Figure 10).

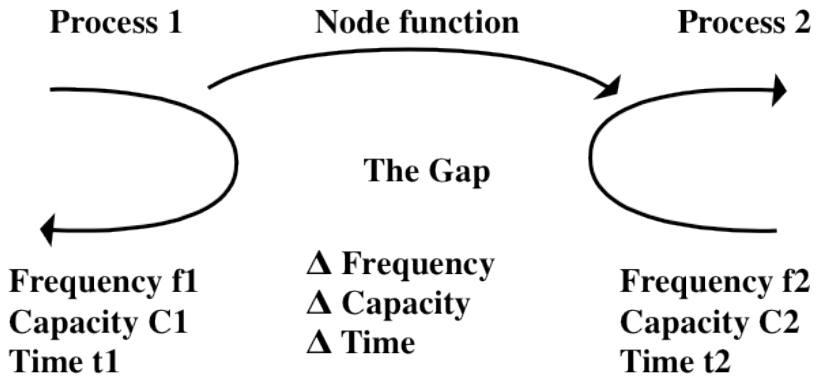

Figure 10: The function of the terminal, adapted from Hultén (1997)

Furthermore, the operator of the torrefaction plant can be compared to distributors in supply chains, for which Jonsson (2008) described the function of the distributor in terms of overcoming a number of gaps, of which the following are relevant for this thesis:
"The pace gap" that arises because customers do not acquire and consume at the same places, at the same times and at the same intervals as manufacturing companies produce
"The distance gap" that arises because producers are located in a few places whereas customers are more numerous and widespread in the market

"The quantity gap" that arises because companies for financial reasons produce and deliver in different quantities per time than individual customers purchase and consume.

The distributor creates a number of utilities, for which Jonsson (2008) has defined:
"Form utility" which represents the added value created through refinement of input goods to finished products
"Place utility" which represents the added value created through making products available for acquisition at the right place
"Time utility" which represents the added value created through making products available for acquisition at the right time
"Ownership utility" which represents the added value created when ownership rights or right of use of a product delivered are transferred to a customer.

3.4 Supply chain design

In order to provide support for constructing a torrefaction configuration framework, a literature review was performed, using the search string "*supply chain design"* followed by snowballing to identify important supply chain design papers. Below follows a short recap of 6 important works. A comparison of the findings with respect to purpose, approach and outcome can be seen in Table 3.

In order to "*devise an effective supply chain strategy"*, Fisher (1997) considered the nature of the demand of the product as the starting point. Aspects of demand included product life cycle, contribution margin, product variety, average margin of error in the forecast at the time production is committed, average stockout rate, average forced end-of-season markdown as a percentage of full price, and lead time required for made-to-order products. Based on these aspects, products can be grouped into functional products with predictable demand, and innovative products with unpredictable demand. These groupings serve as a basis for deciding the supply chain strategy. The outcome of the paper is a framework where a functional product aligns with a physically efficient supply chain whereas innovative products align with a market responsive supply chain.

Payne and Peters (2004) addressed supply chain design as a matter of selecting the "best" supply chain based on achieving the right balance between the required levels of customer service and the total costs of supplying that level of service. In order to achieve this, companies need to match the product with the type of distribution channel delivering the products. A key issue is to decide where to hold stock in terms of dispersed, centralised or only finish to order. The approach used was a product characterisation model based on key attributes, which determines supply chain design. The key attributes comprised volume, volatility (demand variability), orderline value, frequency of orderliness, orderline weight, substitutability of a product and number of customers buying each product. The outcome of the paper was a supply chain design matrix, based on key attributes to determine the supply chain strategy in terms of dispersed stock model, central stock models or finish to order models.

Christopher et al. (2006) addressed supply chain design for global operations. This was done based on a segmentation of products (standard or special), demand (stable or volatile) and replenishment lead-times (short or long). It was argued that because predictability and product times are related, it is possible to simplify the taxonomy to contain just two dimensions: predictability and replenishment lead-times. The outcome of the paper is a framework, consisting of a 2*2 matrix where each cell corresponds to a specific supply chain strategy in terms of lean, agile or leagile.

Pagh and Cooper (1998) addressed supply chain strategies in terms of the concepts of postponement and speculation. The essence of postponement is to perform differentiation at the latest possible point. The essence of speculation is to perform differentiation at the earliest possible time in the supply chain in order to avoid cost. The result of the paper is a framework, which can be used for profile analysis in order to assist managers in selecting between postponement or speculation strategies. These were based upon a number of decision determinants, for which it was stated that: "*When selecting determinants it is essential that the selection is based on each determinant's relevancy for choosing the best P/S speculation strategy."* The chosen determinants were within three categories: (1) product, (2) market and demand, and (3) manufacturing and logistics. Product determinants included life cycle (stage, volume and cost/service strategy), product characteristics (product type and product range) and value (value profile, monetary density). Market and demand included relative delivery time, delivery frequency and uncertainty of demand. Manufacturing and logistics included economies of scale and capabilities.

The goal of Vonderembse et al. (2006) was to provide insights to organisations that design supply chains to manufacture discrete parts. In order to design a supply chain it is essential to understand and differentiate between product types in terms of standard, innovative and hybrid products. Based on the stage in the product life cycle (introduction, growth, maturity and decline) a framework for supply chain design was proposed. This consists of strategies for supply chain design in terms of: (1) lean supply chains, (2) agile supply chains, (3) hybrid/lean supply chains and (4) hybrid supply chains.

Sunil (2003) aimed at describing a framework for designing the distribution network, from supplier to customer. The approach taken was to describe how different performance factors influence the distribution network design, which can be described in terms of (1) customer needs that are met and (2) cost of meeting customer needs. As argued, customer needs consist of many components, and the focus was on those measures that are influenced by the structure of the distribution network: response time, product variety, product availability, customer experience, order visibility and returnability. Supply chain costs were defined as those affected by changing the distribution network: inventories, transportation, facilities and handling. The outcome of the paper was a discussion of design options with regard to the factors for six different distribution networks based on: (1) where products were delivered or picked up, and (2) whether flow was through an intermediary or not.

Table 3: Comparison of supply chain design papers

Paper	Purpose	Approach	Outcome
Payne and Peters (2004)	Address supply chain design	Volume, volatility (demand variability), orderline value, frequency of orderliness, orderline weight, substitutability of a product and number of customers buying each product	A design matrix, where supply chain determinants are used to determine supply chain strategy in terms of dispersed stock model, central stock models or finish to order models
Sunil (2003)	Describe a framework for designing the distribution network in a supply chain, from supplier to customer	Various factors influencing the choice of distribution network (response time, product variety, product availability, customer experience, order visibility and returnability	A description of design options for a distribution based on where products were delivered and whether flow was through an intermediate or not
Vondere mbse et al. (2006)	To provide insights (a framework) for designing supply chains	Product types (standard, innovative and hybrid products) and product life cycle (introduction, growth, maturity and decline)	A framework for supply chain design in terms of lean, agile, hybrid/lean and hybrid supply chains
Fisher (1997)	Address the issue of devising a supply chain strategy	Aspects of demand, which results in grouping of functional and innovative products	A framework, where functional product aligns with a physically efficient supply chain whereas innovative products align with a market responsive supply chain.
Christop her et al. (2006)	Address the question of supply chain design for global operations	Products (standard or special) demand (stable or volatile) and replenishment lead-times (short or long)	A framework for choosing between lean, agile, and leagile supply chain strategies
Pagh and Cooper (1998)	Address supply chain strategies in terms of the concepts of postponement and speculation	Determinants within (1) product, (2) market and demand and (3) manufacturing and logistics	A framework to be used for profile analysis in order to assist managers in selecting between postponement or speculation strategies

Based upon this review, two major issues can be observed:
1. Firstly, in comparison with this thesis, which addresses variations in configurations for one type of product (biomass), the design issue in these papers covers a rather wide range, e.g., different types of products. Hence, it is justified to further specify the design scope within this thesis. Thus, the phrasing supply chain configuration is used to describe the scope, a subdomain with supply chain design. In the literature, the phrasing configuration seems to be considered somewhat more narrow than supply chain design, e.g., Graves and Willems (2005) treated supply chain configuration as an issue regarding how to locate inventory among nodes in the physical flow of goods. Similarly, in this thesis, configuration refers to the physical flow of biomass and how nodes and links are coordinated in supply chains. Firstly, the justification of this research scope is the cost of transport and handling for biomass, which is high compared to fossil fuels such as coal (Gold and Seuring, 2011), which highlights the importance of focusing on the physical flow. Secondly, given that the research in this thesis addresses technology altering product properties in nodes in the supply chain, the flow aspect is obviously relevant to address.

2. Secondly, supply chain design is a rather broad term that can have different objectives. Furthermore, there are a number of different approaches used for describing the supply chains and subsequently determining supply chain design, in terms of "performance factors", "product characteristics", "decision determinants" or "attributes determining supply chain design". This is to some extent an issue of labelling and to some extent based on what the objective of each paper is. However, it is important to identify and capture the *characteristics* of the supply chain in order to propose relevant configuration aspects, e.g., which determinants or *attributes* to address. For example, using the same aspects as in these papers, e.g., product returns, would be not be fruitful, as there are no product returns within biomass to energy supply chains. However, some aspects are often repeated, and that is regarding (1) the nature of demand and (2) product characteristics, and these will hence be used in this thesis, but adapted to the biomass supply chain context.

Furthermore, a drawback of these papers is that many of the "design determinants" are often somewhat arbitrarily proposed, and it is left to the reader to trust the design approaches presented. Hence, in order to provide a valid transparent foundation for supply chain configuration, it is justified to thoroughly address supply chain characteristics through appropriate methods such as rigorous literature reviews and interviews. Characteristics are in this thesis used as a way of capturing the essence of supply chain, which provides a platform for analysing how process technology can be configured. Hence, this provides a justification for the importance of research question one.

3.5 Current body of knowledge

The biomass-to-energy supply chain can be classified into three parts: upstream, midstream and downstream (An et al., 2011), which is similar to the division made by Sandersson (1999) who identifies up-stream supply, conversion and down-stream provision. Upstream, which is the focal part in this thesis, is viewed as the part that supplies biomass to energy production. Midstream refers to energy conversion in power plants and downstream refers to energy

distribution to consumers of energy. The purpose of the following section is to review the current body of knowledge regarding configuration of biomass-to-energy supply chains. This provides a context and a foundation for understanding of the supply chains in which the torrefaction process will be used. The review addresses different stages in the supply chains, ranging from feedstock to energy producers. The review is organised around describing attributes of the different stages, identification of central factors affecting cost and describing factors that influence supply chain configuration.

Different types of biomass are in general separated in the forest, into stemwood and forest residues, which are used to make different products and for different purposes. In Figure 11, a number of existing biomass supply chains with respect customers of non-energy products, coal CHP, households and biomass CHP are depicted. These are examples of supply chains, and there are a number of issues to decide upon, e.g. vehicle mode and selection. Hence, in order to provide contextual knowledge regarding biomass-to-energy supply chain configuration, a number of different issues within each stage is addressed in the review below.

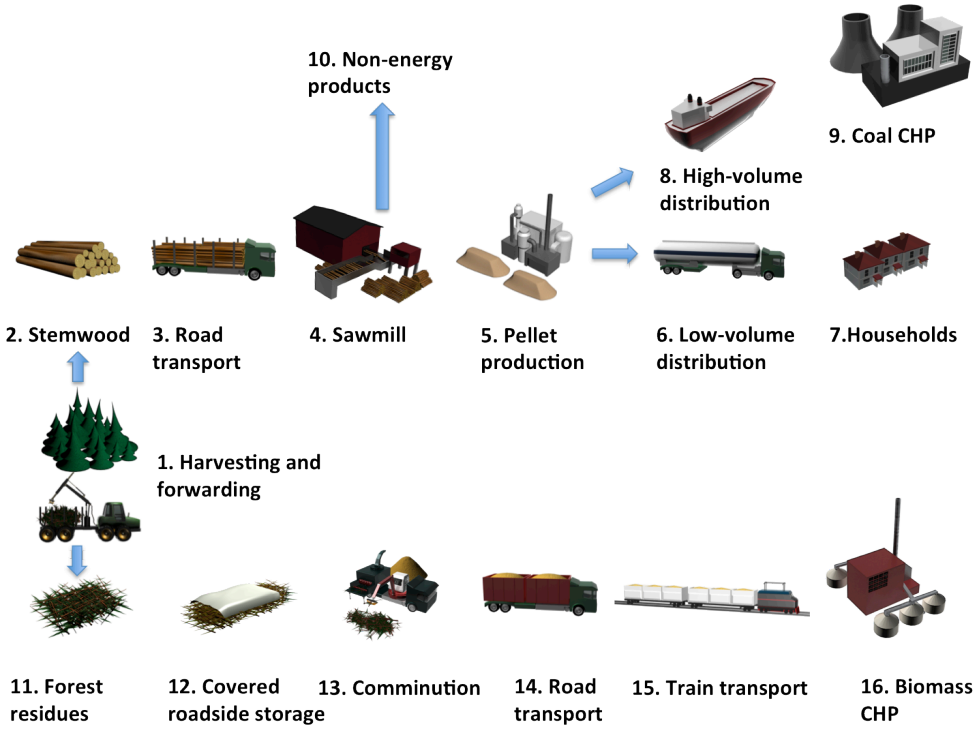

Figure 11: Biomass supply chains

3.5.1 Feedstock

Feedstock characteristics differ on a number of attributes, which is related to the type and location of feedstock. Feedstock for energy production can be procured either directly from the forest, e.g. forest residues or from sawmills, in the form of by-products such as sawdust. Depending on origin, which e.g. can be described in geographical location or type, feedstock has a number of different attributes, which have implications for procurement by torrefaction and energy-producing companies.

Geography: Biomass can be classified in terms of geographical dispersion. Primary feedstock is acquired directly from the source, i.e., the forest, whilst secondary feedstock in the form of by-products consists of refined biomass or return wood. The main logistical difference is that secondary feedstock is sourced from a single geographical point, whereas primary feedstock has a geographical spread, and requires a different approach to sourcing and inventory control.

Ownership: Forests from which feedstock is provided are owned and controlled by either large corporations or by small private owners. Regarding accessibility to these resources, previous research suggests that buyers must be very active in their contact with private forest owners in order to convince them to sell (Bohlin and Roos, 2002).

Competition and integration: In some cases, the wood fuel market is closely integrated with the forest sector, either through business relations or due to the dependency to supply feedstock from one sector to the other (Roos et al., 1999). Feedstock can be used by a number of different industries, and as a consequence, there is often a competition of raw material in European countries between pellet producers and combined heat and power plants (Monteiro et al., 2012), but also from non-energy sectors such as the particleboard industry (Selkimäki et al., 2010). Integration and competition are of high importance in countries where biomass utilisation is well developed, e.g., in Europe, whereas in low-cost biomass countries competition and integration is low. Finnish pellet producers, for example, are dependent on the forest sector, as lack of feedstock has been related to the decrease in the number of sawmills that has caused pellet plants to run below full capacity (Selkimäki et al., 2010).

Cost: The fourth factor is the cost of feedstock, including transport and storage. Wolf et al. (2006) noted, for example, that a cheap surplus of feedstock seems to be one of the major drivers for pellet production. Feedstock cost, which can vary significantly across regions and over time, is a major driver behind international trade. Low cost of feedstock in combination with large feedstock potential favours countries such as Canada and Brazil for producing and exporting refined biomass (Junginger et al., 2008, Heinimö and Junginger, 2009).

Quality for an end user: Feedstock can also be segmented based upon a number of quality parameters such as moisture content, contamination and ash content. Some feedstock such as stumps is only desirable for some types of customers, e.g., large CHPs who are flexible in receiving a fluctuating quality of feedstock, but not for customers not being able to handle contaminations.

Quality for logistics operations: Finally, feedstock has different quality, e.g. in terms of different energy density, which is a function of moisture content and bulk volume. This has implications for transportation and handling efficiency. However, transport efficiency is not only a function of energy density, it is also a function of weight restrictions of different transport modes. E.g., for trucks, the loading capacity can be as low as 35% for TDB, based on how well the carrier is adapted to volume or weight and how the load is arranged on a truck. Train transportation is to a much smaller extent limited by weight, and has about a 70-

80% fill rate for TDB. Whereas road and rail transport is hampered by restrictions, sea shipping reaches or is close to 100%, depending on the design of the ship.

3.5.2 Harvesting and forwarding

Harvesting and forwarding can be arranged in different ways and is influenced by time constraints. For forwarding, there are a number of factors that affect the selection of forwarding equipment and the cost of forwarding.

Time constraints: Given that the major share of the economic value of the tree is the stem, which is purchased by pulp-and-paper industries, it is that sector that has the major say on when the trees should be harvested. Forest residues are seen as a by-product and bioenergy production seldom has a major influence on decisions made in the forest (Richardson, 2002). From a logistical point of view, stem wood is a pull system, whereas forest residues can be seen as a push system, and as a result, storage has to be done throughout the biomass-to-energy supply chain to bridge the gap between supply and demand. Furthermore, when the forest is harvested, forest residues are left to dry in general for at least one summer to increase the quality (increased calorific value and improved transportation properties due to decreased moisture content) and to ensure sustainability in the forests by letting needles fall off. Hence, these issues pose time constraints on the supply chain configuration.

Selection of forwarding equipment: Forest residues can be forwarded (transported in forest), comminuted, uncomminuted, or put into bundles. Bundling improves the transport efficiency in the forest and can, under some conditions, be more profitable for the entire supply chain of forest residues (Johansson et al., 2006). This, however, puts some requirements on the supply chain such as the ability to perform cost-efficient comminution by the customer. It has been shown that under Finnish conditions bundling is the most competitive method for when road distance exceeds 60 km (Kärhä and Vartiamäki, 2006), which, however, requires that the end-user has the possibility to perform comminution. The bundles have other logistical advantages besides increasing transport efficiency, such as the ability to use conventional roundwood machines and trucks for transport to the customers (Johansson et al., 2006). When choosing machinery, the choice is not always based entirely on cost, as it can be the case that loggers want more robust systems. Safety and environmental concerns can influence the choice as well (Van Belle et al., 2003).

Cost of forwarding: In general, the cost of forwarding is dependent on which type of vehicle is chosen, which in turn often depends on regional circumstances such as tree species, terrain, topography, season, load size, stack volume, distance between stands, volume per ha, forwarding distance, and landing type (Asikainen and Kuitto, 2000).

3.5.3 Storage

Storage is most often required in order to bridge the gap between supply and demand and to facilitate adoption to varying market conditions in general. The configuration of the storage has implications for cost and quality of feedstock.

Dimensioning of storage: Biomass can be stored in forest, at roadside, in terminals or at customers. Key parameters affecting cost are type of storage, time of storage, volume to be stored (Gold and Seuring, 2011) and height of storage piles (Jirjis, 2005). The shape in which biomass is stored is of significant importance, as comminuted forest chips can cause remarkable greenhouse gas emissions (Wihersaari, 2005). An important issue within storage is whether forest residues should be stored with covered storage or not. Covered storage comes at a cost, is done at roadside, but in general improves the quality. It has been recommended that when forest fuel has been comminuted, it should only be stored for a week. Finally, storage cannot been seen in isolation, e.g., Allen (1998) noted that optimisation of a harvesting system could lead to an expensive storage system and fail to deliver the quality desired by the customer.

3.5.4 Comminution

Biomass is comminuted in order to increase transport efficiency and to prepare it for energy conversion. How and where it is done has implications for subsequent transport and handling cost, and the quality in which it arrives to customers.

Resource selection for comminution (type, place, and time): There are two principally different technologies for comminution: chipping using knifes and grinding using hammers. Spinelli et al. (2012) compared the two techniques and it was shown that chipping has higher productivity and results in better chip quality and that grinding should only be used when feedstock have high levels of contamination. Forest fuel can be comminuted in the terrain, at roadside, on terminals or on plant side. Scheduling of vehicles used in the biomass-to-energy supply chain needs to be done both in time and in place. Biomass can be comminuted in the forest area, at roadside, at terminal or at customer. There is a trade-off between transportation, timing of comminution and storage efficiency. This is due to three facts: (1) comminution equipment reaps advantages from economies of scale (Kanzian, 2009), e.g., most efficiently done at terminals, (2) but early comminution in the supply chain (e.g., roadside) allows for efficient transportation; however, (3) due to the fact that biomass is a biological material it should be used within one week after comminution in order to avoid significant substance losses (Wihersaari, 2005).

Factors affecting cost for comminution: Factors that affect efficiency of comminution are assortment, organisational setup, operators, local environment, weather (Röser et al., 2012), harvesting conditions, roadside landing capacities, availability of production machinery and type of forest chips produced (Kärhä, 2011). In addition, a major factor in chipping is delay – mechanical, operator and organisational delays, which on average account for 24.2% of total work time (Spinelli and Visser, 2009). Furthermore, the selected comminution system must be adapted to the specific customer, e.g., only some customers have the possibility and are allowed to perform comminution themselves.

3.5.5 Road transportation

Given that transportation cost accounts for a significant share of procurement cost, selection of transportation trucks is important, and is influenced by a number of factors.

Selection of trucks: There are a number of different vehicles available for the *transport* of forest fuel. Different vehicles for road transport are suitable under different conditions; when distances are short, for example, it can be profitable to transport loose residues (Ranta and Rinne, 2006) (Asikainen, 2001) whereas on long distance transportation, a bundling system can be more profitable (Johansson et al., 2006). Furthermore, selection of transport modes is not only an issue of operational efficiency; there are cases when there are external reasons affecting the choice. There are cases when public relations are important; for example, container systems have been reported to be chosen in order not to spread too many forest chips at roadside in urban areas (Björheden, 2000).

Cost of transportation: In a review, Gold and Seuring (2011) identified mass, volume, energy density, travel time, distance, speed, road properties and infrastructure as major factors affecting road transport cost. Optimisation of travel routes is one way to reduce transportation costs and it is essential to schedule trucks according to the number of round trips they can make each day (Rogers and Brammer, 2009). Bartering volumes between suppliers has been shown to have a high potential for reducing transportation distance and hence transportation costs, e.g., for an Austrian case it was possible to reduce transportation distance by 26% and transportation cost by 23% (Rauch et al., 2010). The utilisation rate of the truck is of significant importance, e.g. due to factors such as the possibility to get a back-haul (Rauch and Gronalt, 2011).

3.5.6 Network design

A key issue to decide upon is the network structure, e.g., how links and nodes are coordinated to constitute supply chains; see Figure 12 for a number of possible routes. Network design is a function of a number of aspects and must be adapted to the specific case.

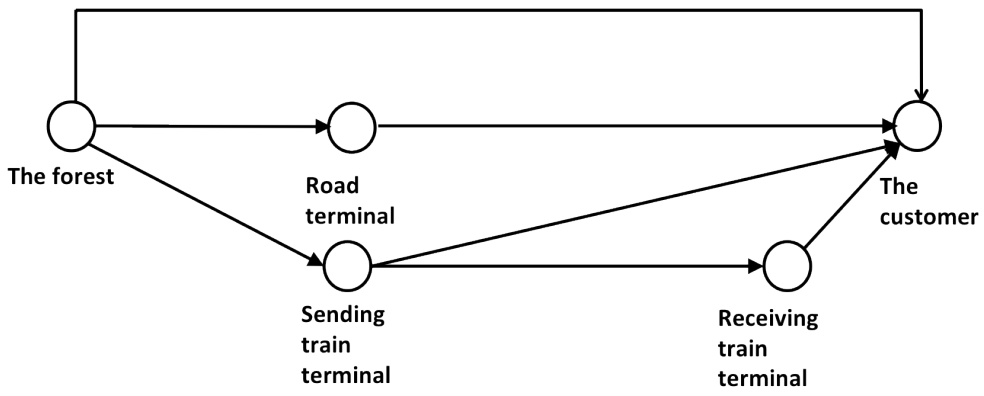

Figure 12: Alternative supply chain routes

Network structure: A key issue to decide upon is to have direct supply from roadside to power plant or handling via terminals. For forest fuel it is often concluded that system configuration should be as simple as possible, e.g., minimising the number of handling steps (Eriksson and Björheden, 1989, Hall et al., 2001, Kanzian, 2009) as each extra operation is associated with cost. It is hence important to have a systems perspective, e.g., dealing with transports and processes at the same time, in order to understand the wider implications of decisions made at each stage in the supply chain. When designing a supply chain, site-specific matters such as regional characteristics of resources and infrastructure have to be taken into account (Ranta, 2005). It can be necessary to use a number of systems in order to ensure the supply throughout the year (Allen, 1998). A combination of direct supply via intermediate storage can be desirable (ibid).

Drivers for using terminal supply: A number of reasons for choosing terminals have been identified. One of the major benefits of terminals is that forest fuel can be stored in order to manage the gap between supply and demand that takes place throughout the year (Gunnarsson et al., 2004). Terminals are often required to hold a minimum level of storage of forest fuel in order to be a protection against the variability in demand with increased cost as a result (Gunnarsson et al., 2004). Furthermore, transporting via terminal can be advantageous as central and larger chipping machines also have operational advantages through reaping advantages from economies of scale. Finally, terminals can be used to mix raw material into a required uniform fuel (Björheden, 2000).

Multiple transport modes: Transport of forest fuel can gain advantages from using a combination of transport modes, but the distance needs to exceed a certain length in order to overcome the fixed components of two transport modes and the transhipment costs. It has been shown that under North American settings it is profitable to transport forest chips through the combination of train and truck when the distance exceeds 145 km (Mahmudi and Flynn, 2006) and about 150 km transportation distance under Finnish settings (Tahvanainen and Anttila, 2011). This is, however, from a theoretical point of view, and local infrastructure needs to be taken into account (Mahmudi and Flynn, 2006). This is in line with the conclusion that train transportation in Finland is hampered by the lack of railway terminals and terminals at energy plants (Tahvanainen and Anttila, 2011). If a buffer is needed in the supply chain, railway transportation might have great potential even if distances are shorter than 100 km (ibid).

Cost of train transportation: Major factors affecting the cost of rail transportation in general are the cost of electricity to run the train and the investment cost for the engine (Flodén, 2011). Hence the utilisation rate of the train is of high importance and utilising the train all through the year and achieving back-haul can lower the cost significantly. Other factors likely to influence rail transportation are the structure of the transportation network, the time period, cycle length and size of unit trains (Osleeb and Ratick, 2010). A reason for choosing rail transportation in favour of road is the lower external cost of train transport compared to road transport. A large CHP located in a city

requires a high number of trucks delivering biomass, and a train supply system could lower the emissions and reduce noise (Mahmudi and Flynn, 2006). The cost of transport is also affected by carrier selection (type of load unit) and how well it is designed in order to utilise the vehicle's loading capacity.

Cost of terminal handling: The cost of handling biomass at a terminal is dependent upon a number of factors. Two of the most important factors for the efficiency of a terminal are the scale and scope of the terminal. If a terminal can perform activities such as storage, comminution or mixing of peat and forest fuel, a truck-train supply can be competitive compared to direct supply via truck at distances even smaller than 135km (Tahvanainen and Anttila, 2011). This is a relatively short distance, compared to, for example, non-bulk goods transported via intermodal terminals where the distance in general needs to exceed 500km in order to be viable, although distances down to 250km can be competitive under favourable conditions (Flodén, 2007).

3.5.7 Refinement of biomass

A number of decisions made at torrefaction plant level have wider implications for the supply chain. As a basis for further evaluation, this section addresses the current body of knowledge, both with respect to torrefaction plants but also for different types of bioenergy plants.

Plant configuration: Common to bioenergy plants is the quest to deal with the trade-off of economies of scale of the plant itself (cost of production), and the diseconomies of acquiring large volumes of feedstock from distant locations (cost of inventory and transportation). The logistical constraint relates to feedstock as a distributed resource (low volume at dispersed locations). The larger a CHP is built, the longer the average transportation distance and hence increased haulage cost (Cundiff et al., 2009). Accordingly, a torrefaction plant must be located according to logistical efficiency but also according to production economics parameters. Smaller pellet plants using by-products for pellet production are often co-located with their supplier in order to minimise transportation costs (Selkimäki et al., 2010). In these cases, pellet production is seen as a by-product from the main business (ibid). Besides co-locating for logistical advantages, two other major advantages can be reaped from integration of plants that produce different kinds of products: 1) By sharing existing structures the investment costs are lowered; (2) through energy and material exchange between processes in the plants and by using the same personnel and equipment, the operating costs can be lowered. Torrefaction plant decisions also have to be made on storage layout such as inventory levels of feedstock. Just-in-time reduces storage requirements but might not be possible due to road accessibility, which could lead to a shortage of feedstock and production disruptions (Sultana et al., 2010).

Operational decisions: Pellet quality is a function of not only feedstock selection but also process decisions. Shang et al. (2012) have identified a relationship between process decisions and quality of pellets by, e.g., high torrefaction temperature that results in higher transport weight and energy loss, and negative relationships between temperature and durability of pellets. Traditional pellets are classified into three categories (A1, A2, and B), the

quality of which is contingent on parameters such as ash content, heating value and net calorific value, which in turn affect the final energy conversion process and maintenance of boilers. The quality parameters of torrefied pellets are important to supply chain configuration for at least three reasons: *durability*, which has effects on handling and storage, *degree of hydrophobicity*, which has effects on storage, and *energy density*, which has effects on transport efficiency.

Cost of bioenergy plants in general: Among the factors affecting cost of bioenergy plants is size, e.g., pellet plants (Nilsson et al., 2011) and CHP (Flynn et al., 2003), which benefits from economies of scale. Large-scale plants reap advantages from the high utilisation rate of equipment and the fact that when scaling up plants, the increase in staff is not proportional to the scale (Nilsson et al., 2011, Sultana et al., 2010). For large scale plants, the costs of feedstock and energy account for the largest share whereas personnel and capital have a smaller share (Nilsson et al., 2011). In order for a pellet plant to reach long-term success, it is important to have a combination of a secure market of large-scale but low profitability customers and a near small-scale market of high profitability customers (Wolf et al., 2006). However, increasing the scope of customers requires investment in different logistical resources: bulk-handling systems for large customers and plastic bags for smaller customers. Finally, pellet production can reap economic and environmental advantages from integration with CHP, c.f. Song et al. (2011).

Cost of torrefaction plants: A few recent studies have assessed the cost of constructing and operating *torrefaction plants*. Torrefaction investment cost reaps significant advantages from economies of scale and should exceed 40 MW_{th} (Uslu et al., 2008). The operating availability has been argued as perhaps the most important parameter affecting production cost (Shah et al., 2012, Uslu et al., 2008), but moisture content is also of significant importance (Shah et al., 2012). Another important parameter affecting torrefaction cost is torrefaction severity (i.e., temperature and residence time), which when increased had a negative impact on production cost (ibid).

3.5.8 Distribution of refined products

The internal operation processes at the torrefaction plant and the product itself (i.e., the outcome of the process) must be aligned with the distribution system, i.e., the ability to ship in a variety of volumes to different locations at different points of time. Based upon two generic situations, high-volume distribution and low-volume distribution, a number of important attributes have been identified.

High-volume distribution:

Transportation: Distribution is to large scale users done through intercontinental shipping with Panamax or Handymax vessels, using ports for storage up to 200,000 tons and up to 10,000 tons of storage at plant (Sikkema et al., 2011).

Contracts: Trading of pellets is highly dependent on transportation cost, which plays a significant part in Transocean supply chains (Sikkema et al., 2010) and is sensitive to the price fluctuations of freight transport. There have been cases where the transatlantic trade of pellets has been hampered due to price fluctuations of freight rates (Junginger et al., 2008). The type of chartering

contract is also of importance, as some suppliers have long-term contracts making them immune to price roller coasters (ibid).

Market dynamics: Pellets is a dry bulk commodity, which is subject to the seasonal fluctuations in freight spot rate. Freight rates have been found to vary from -18.2% to 15.3% in individual months within a year (Kavussanos and Alizadeh-M, 2001). This has effects on tactical shipping operations such as timing of dry-docking, chartering strategies and switching between freight markets (ibid).

Infrastructure: One of the major barriers to increased trading is infrastructure both in sending and receiving countries (Junginger et al., 2008). Some end users of pellets, such as CFPP, are capable of receiving large ships whereas other plants require transhipment into smaller barges, or road/rail transport due to infrastructural matters, which puts requirements on the supply chain configuration in terms of intermediate storage. Capacity within transportation corridors can be an issue as well, as inland waterways limit the size to small ships but also, more importantly, some railway corridors are congested (van Dam et al., 2009).

Quality: Quality of white pellets is a major issue for the distribution system. During long distance transports, pellets can disintegrate (Selkimäki et al., 2010). Furthermore, covered storage is required in order to avoid remoistening. However, for torrefied pellets, there is the possibility to a much larger extent of control transport quality due to the hydrophobic properties. Controlling the quality through the whole production, delivery and handling chain is essential for pellet sustainability and viability compared to other fuels (Selkimäki et al., 2010).

Low-volume distribution:
For small-scale users (bulk or plastic bags), transportation is done by truck, primarily from smaller domestic plants, and is distributed via retailers, or through direct supply from plant to households based on annual delivery schemes. Given the low value of biomass, distribution is limited to a maximum distance; for example, 300 km under Finnish settings (Selkimäki et al., 2010). A few years ago it was noted that quality (in terms of standardisation) was a major barrier to increased utilisation, but that a standard was on its way (Junginger et al., 2008) which at present is about to be put into place. A barrier that is hindering intercontinental distribution to small-scale users is that the infrastructure required in receiving countries requires distribution (ibid). It has been shown that time has a negative impact on durability of white pellets stored in plastic bags (Lehtikangas, 2000) but the effects on TDB have yet to be shown.

3.5.9 Energy production

Energy producers range from household production in small-scale boilers to large coal-fired power plants and differ with respect to number of attributes, which will influence how the supply chain is configured.

Energy Production pattern: Energy producers have different energy production patterns (e.g., base, mid or peak load) in terms of how they produce energy

throughout the year. Some plants are operated at about the same load almost the entire year, often using forest residues or household waste, and are in general defined as base-load plants. Other plants uses e.g. pellets, and are operated part of the year, and there is a difference between minimum, average and maximum energy production. These are sometimes defined as mid-load plants. In order to cover certain spikes in demand, smaller plants, e.g. oil boilers are used, and are often defined as peak or top-load. These different plants require different supply systems in order to satisfy the demand; for example, when it comes to storability of energy carriers used for energy transformation.

Contracts: Large customers use long-term contracts (up to three years) but also purchase on short-term markets (Sikkema et al., 2011). Medium-size customers have long term-contracts as well as short-term deliveries from daily spot markets (ibid). Customers have different requirements on supply security and contracts. CFPP producing base-load energy cannot afford to run out of coal and require long-term contracts or cooperation whereas mid-load producers have the ability to make adjustments according to market circumstances (Li, 2010). Heterogeneity of quality of coal has previously been an issue for coal purchasers, but technological advancements have made it possible for increased spot trading, and as a result coal buyers are more willing to trade security for price (ibid). Another factor favouring spot contracts is an increase in number of supply countries, which makes supply security less of a concern (ibid), favouring shorter contracts.

Quality: Different customers have different quality requirements on feedstock. In general, small-scale customers have the highest and large-scale customers have the lowest quality requirements.

Accessibility: Large-scale customers have different abilities to receive and store pellets depending on location and investments made. When pellets are used for co-firing, they often make use of coal-infrastructure, but there are also cases when custom-made pellet unloading stations are built adjacent to the power plants (Junginger et al., 2008).

4 Summary of appended papers

This chapter summarises the four appended papers with respect to approach, findings and contribution.

4.1 Paper I - "Energy resources – trajectories for supply chain management"

Approach:
Even though there is plenty of research on the fields of SCM and energy, there has been very little on the conceptualisation between SCM and energy. Hence, the aim of the paper was to explain how principles of supply chain management (SCM) provide conditions that are important for the transition toward production, access and use of renewable energy resources. The method used in this paper was a structured literature review, followed by a conceptual discussion. This was done by first addressing the scope, the relationship between energy and SCM and a changing context that research must respond to. That was followed by a deeper discussion of the interplay between SCM and Energy, focusing on major themes within SCM: activities, benefits (e.g., performance) and components (e.g., structure) found within the literature.

Findings:
Based on the literature review and a conceptual approach discussion, three trajectories were proposed (see figure 13). The phrasing "trajectory" is a metaphor used to describe why and how a framework, explaining the relation between energy and SCM, provides direction for future research. However, with respect to this thesis, the paper as a whole and the trajectories only serve as justification and foundation for carrying out the research, e.g. describing the importance of an upstream perspective seen from the energy sector. Rather, the primary contribution is the conceptualisation of important themes of biomass-to-energy supply chains, which comprises:

Structure:
Geographical dispersion of up-stream supply: Due to the geographical dispersion of raw material (low volumes of feedstock, spread over large areas, controlled by many small actors), consolidation of flows becomes a key task.
Fluctuations in consumption: Fluctuations in energy consumption occur in the short and long term, due to weather fluctuations and seasons, and due to changes in demand pattern. The supply chain needs to be organised to manage these fluctuations.
Relationship management. Links must be established both on vertical levels and on horizontal levels, e.g., to manage the dispersion in different types of biomass used for energy production.

Operational performance:
Volume: By consolidating flows, handling and transportation resources can reap economies of scale. Furthermore, given that biomass is a low-valued good, the biomass to energy supply chain needs to share supply chains with other types of products, e.g., to share fixed and operative costs of terminals used for transhipment.

Time: Biomass is a perishable good, and an important decision within supply chain configuration is to deal with the trade-off between storage efficiency and scheduling of logistics resources.
Capacity utilisation: Cost of procuring biomass can under some circumstances be lowered by sharing equipment with non-energy products.

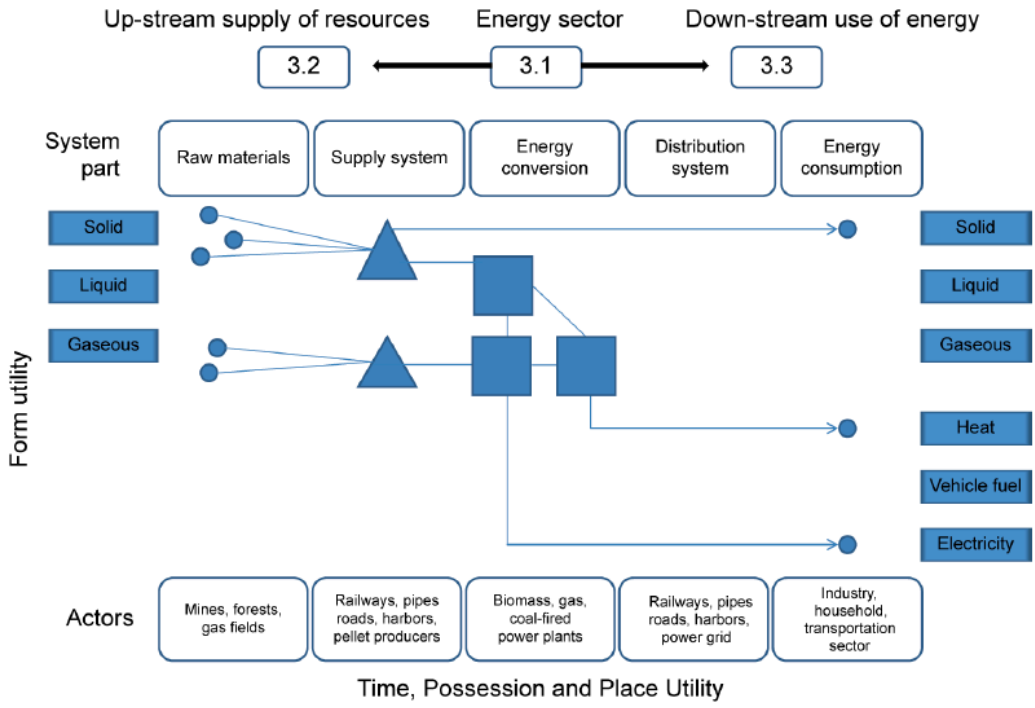

Figure 13: Trajectories for energy supply chain management

Contribution:
For academia, the key contribution was the three identified trajectories, which provides direction for future research for supply chain management of renewable energy.

4.2 Paper II - "Factors influencing the configuration of biomass-to-energy supply chains – The case of forest fuel"

Approach:
Understanding which factors influence an effective and efficient configuration of the supply chain is of significant importance in order to make biomass-to-energy cost competitive. The aim of the paper was hence to complement the current body of knowledge within the scientific community regarding factors influencing the configuration of biomass-to-energy supply chains. This was done through a literature review and through interviews with actors in biomass-to-energy supply chains: producers of forest fuel, handling and transportation companies and energy companies. As earlier argued, the justification for not only performing a literature review was a possible gap in knowledge due to a gap in research methods used to address the issue. Hence, an inductive approach using semi-structured interviews was taken.

Findings:
From the literature review, the factors influencing the configuration were broken down into two groups: external factors and efficiency factors. External factors comprise those that need to be taken into account, which are often constraints of supply chain configuration. Efficiency factors comprise contextual aspects of the biomass-to-energy supply chain, which basically describes factors that influence efficiency within a node, link or the overall network configuration. The summary from the literature review can be seen in Table 4.

Table 4: A summary of literature findings of factors influencing supply chain configuration

Activity	External factors	Efficiency factors
Harvesting and collection	• Supply is often of push type • Handling and transportation integration with non-energy supply chains • Time constraints • Customer ability to comminute • Scattered geographical distribution of forests	• Forest geography characteristics (tree species, terrain, topography, season, load size, stack volume, distance between stands, volume per ha, forwarding distance, landing type)
Comminution	• Type of chips to be produced • Customer capabilities to comminute • Requirements to comminute at a certain location to increase transport efficiency	• Quality of biomass • Location and economies of scale • Organisational setup • Operators • Local environment • Weather • Harvesting condition • Roadside landing capacities • Availability of equipment
Storage	• Demand of storage	• Shape • Location • Type • Time of storage
Transport	• Stakeholder preferences	• Biomass properties (bulk volume, moisture content and shape) • Road properties • Vehicle type • Infrastructure • Scheduling of resources • Distance • Fuel cost
Network design	• Storage requirements to bridge supply and demand • Requirements on using a	• Site-specific matters • Infrastructure • Using the right system for

	combination of systems to ensure all around year supply • Physical barriers	the right user • Competition between users • Cooperation within supply chains • Cost of energy

In a similar way, empirical evidence from interviews was analysed and grouped into the same categories. The two bodies of knowledge complement each other. There were no major contradictions between the factors identified in the literature compared to the interviewee's views. A number of issues were similar, e.g., stakeholder preferences were identified in both parts, but affected different aspects within supply chain configuration. However, the interviewees also reported reasons for supply chain configuration that are not extensively dealt with or are only touched upon within the scientific literature. The most frequently repeated and emphasised are: (1) the interaction of forest residues with other types of biomass and also with other product flows, (2) the issue of quality, (3) adapting the supply chain to the specific customer, and (4) a number of business reasons to configure the supply chain in a certain way. A summary of the results can be seen in table 5.

Table 5: A summary of interview findings of factors influencing supply chain configuration

Activity	External factors	Efficiency factors
Harvesting and collection	• Stakeholder preferences	• Shape (green or non-green)
Transport	• Environmental drivers • Other product flows • Quality aspects • Demand on storage • Regional climate • Distance to customer • Direct train access to customers or not	• Making case specific vehicle selection • Size of transportation company • Using vehicles with regard to utilisation rate during the year • Using a combination of vehicles • Using vehicles that can be utilised for other purposes during off-peak biomass season • Back-hauling • Multiple transport modes • Direct train access to customers • Intermodality
Network design	• Stakeholder preferences • Regulations • Seasonality of forest fuel supply and demand	• Other product flows (biomass and non-energy products) • Sharing fixed and operating costs

	• Type of customer • Customer demands and capabilities • Business reasons	• Function of terminal • Utilising terminals with low investment costs
Procurement	• Type and size of energy producer • Storage and comminution capabilities • Flexibility on quality, mix and types of fuel • Business reasons • Demands on delivery service and supply security • Drivers for vertical integration • Climate	• Cooperation with other companies

Contribution:
The identified factors could have implications both for future research and for academia. For academia, the major contributions are:

- Some of the factors can be incorporated into- and evaluated through mathematical models. For example, interaction with other types of supply chains could be evaluated through optimisation models.
- The identified factors comprise a vast list of factors that can serve as a starting point for making delimitations of what has been disregarded in optimisation models.
- The performed study was more broad than deep, and focus was on identification of a vast number of factors rather than on explaining causality for a few in detail. Hence, the identified factors should be further evaluated in terms of causality, for example, in case studies, e.g., how quality issues should be managed in a supply chain perspective.

For the industry the major contribution is:

- The factors provide an overview for actors within biomass-to-energy supply chains that can be used as a starting point for different actors to understand each others' operations and to avoid system sub-optimisation.

4.3 Paper III - "Supply chain configuration for biomass-to-energy: The case of torrefaction"

Research approach:
Torrefaction offers a range of potentially beneficial logistics properties but the actual benefits depend upon how the supply chain is configured to address various elements of customer demand. In order to provide the industry with knowledge of a torrefaction plant in a supply chain perspective, the aim of this paper was to, through a conceptual approach, develop a framework for torrefaction configuration in a supply chain perspective for different types of customers. When all data on torrefaction cost, handling, transportation and

energy conversion becomes available, the theoretic framework provides a good starting point for supply chains to evaluate from an economic perspective. The paper was approached through a literature review of torrefaction, related research fields such as unrefined forest fuel, pellets and coal logistics and prescriptions for configuration derived from SCM.

Findings:
The literature review paper took a supply chain perspective and identified five major steps within the supply chain: (1) feedstock, (2) supply system, (3) production (torrefaction), (4) distribution system and (5) customer demand. For each of the steps, a number of attributes that had implications for supply chain configuration were identified:
Feedstock: Geography, ownership, competition and integration, cost and quality
Supply system: Transportation and handling, network structure and scheduling of resources
Production: Plant configuration, operational decisions and relation between upstream and downstream decisions
Distribution: Transportation, contracts, market dynamics, infrastructure and quality
Customer demand: Type of customer, energy production pattern, contracts, quality and accessibility

Based on the identified attributes and a conceptual argumentation, a framework for *torrefaction configuration*, which is a term referring to decisions regarding the organisation of production as well as upstream and downstream activities, was proposed. The framework was exemplified for three distinct types of customers, which mainly differs on size, energy production pattern and quality demand. The range is from large coal-fired power plants, via medium-sized combined heat and power plants and district heating, to household consumption of pellets. Based on prescriptions for linking supply and demand from SCM, three niches for torrefaction configuration were proposed. For these it was argued that important torrefaction decisions comprise torrefaction plant configuration, product characteristics, feedstock characteristics and distribution systems (see figure 14). How the framework can be used will be further discussed within the analysis chapter.

Supply chain attributes		Type of customer		
		1. Large coal-fired powerplants	2. Medium sized bioenergy plants	3. Households
Demand	Quality	Low	⟷	High
	Energy production pattern	Base-load	Fluctuating	Fluctuating
	Size of customer	Large	⟷	Small
Torrefaction plant configuration	Location driver	Close to cheap feedstock	⟷	Close to low cost production
	Plant Size	Large	⟷	Small
	Function of process	Bridge gap in distance	Bridge gap in time	Bridge gaps in quality and ownership
Product characteristic	Main quality parameters	High energy density	Trade off between high energy density, durability and degree of hydrophobicity	Durability
Feedstock characteristic	Parameter affecting feedstock selection	Low cost	⟷	High quality
	Feedstock competition and integration	Low	⟷	High
	Feedstock location	Low cost country	⟷	Close to market
Distribution system configuration	Inventory strategy	Minimise	Hold stock to bridge fluctuations	Hold stock for speculation
	Transportation mode	Large ships	Small ships, trains, trucks	Trucks
	Trading flexibility	Low	⟷	High
	Network design	Physically efficient	Responsive	Responsive
	Lead time focus	Shorten as long as it doesn't increase cost	Invest to reduce lead-time	Invest to reduce lead-time

Figure 14: A framework for torrefaction configuration

Contribution:

The key contribution for academia is:

- A framework that explicates different elements of supply and demand of torrefaction. This serves as a starting point for evolution of possible supply chain configuration, and as a starting point for further research on torrefaction in a supply chain perspective. The proposed framework

entails a set of propositions, but requires further development through empirical studies, using complementary methods such as interviews or surveys and quantification through techno-economical or optimisation models.

The key contribution for the industry is:

- A framework that can inform decision makers in biomass-to-energy supply chains, in particular at torrefaction plants, and on upstream and downstream implications of their decisions.

4.4 Paper IV - "Analysing biomass torrefaction supply chain costs"

Approach:
In order to assist actors of torrefaction plants in involved in biomass-to-energy supply chain configuration, it is crucial to identify which and how parameters affect the torrefaction supply chain costs. Hence, the objective of the paper was to develop a techno-economical system model to address how logistics and torrefaction parameters affect the total cost (under Swedish conditions) of supplying TDB to a CHP. This was done through a literature review of related research fields to identify possible parameters affecting cost in a torrefaction supply chain. This served as the basis for constructing a techno-economic model of the entire supply chain, ranging from feedstock to the gate of an end-user. The model consists of four sub-models: (1) a supply system, (2) a complete energy and mass balance of drying, torrefaction and densification, (3) investment and operating costs of a green field, stand-alone torrefaction pellet plant, and (4) a distribution system to the gate of an end user.

Findings:
The results show that the torrefaction supply chain reaps major advantages from economies of scale for torrefaction plants up to 150-200 $kton_{DS}$/year and that the cost curve of TDB at the gate of an end user then flattens out (see Figure 15). For the 200 $kton_{DS}$/year torrefaction plant, the cost for the entire supply chain sums up to 31.8 €/MWh_{LHV}, where supply system (including biomass premium) accounts for 59.5% of the system cost, the production cost to pellets accounts for 31.0% and the distribution system for only 9.48%. There are economies of scale for both the torrefaction plant and for the distribution system. When increasing torrefaction plant size from 25 $kton_{DS}$/year to 200 $kton_{DS}$/year, the production cost decreases from 19.8 to 9.88 €/MWh_{LHV} (a 50% reduction) but the distribution cost only drops from 3.62 €/MWh_{LHV} to 3.02 €/MWh_{LHV} (a 16.5% reduction). There are also smaller diseconomies of scale of supplying larger plants, and when plant size increases from 25 to 200 $kton_{DS}$/year, supply cost increases from 16.7 €/MWh_{LHV} to 18.9 €/MWh_{LHV} (a 13.2% increase).

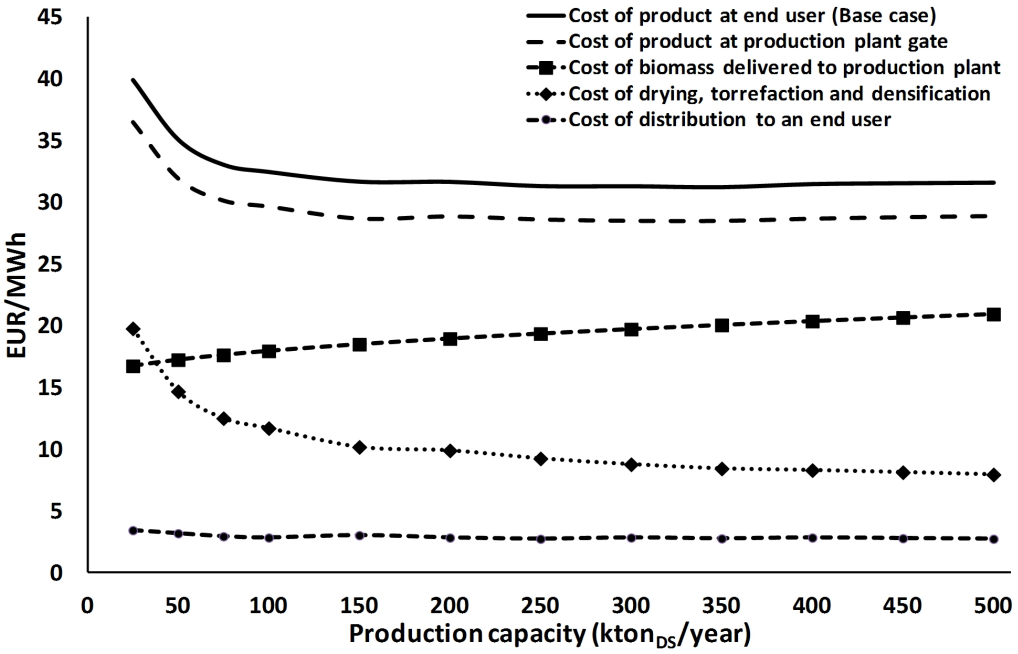

Figure 15: Cost for the torrefaction supply chain

For a 200 kton$_{DS}$/year torrefaction plant, the activities in the system that account for the largest share of the total costs (31.8 €/MWh$_{LHV}$) all belong to the biomass supply system (in total 18.9 €/MWh$_{LHV}$) which are: biomass premium at 4.40 €/MWh$_{LHV}$; comminution at 3.98 €/MWh$_{LHV}$; road transport to torrefaction plant at 3.86 €/MWh$_{LHV}$ and forwarding cost of 3.37 €/MWh$_{LHV}$; see Figure 16. The costs for activities within the distribution systems are rather low, explained by the fact that TDB has very high energy density in combination with efficient rail transport, which keeps transport and handling costs low. Still, the full potential advantages of TDB biomass cannot be utilised due to weight restrictions in road transports, which results in the containers only having a fill rate of about 71% from a volume perspective.

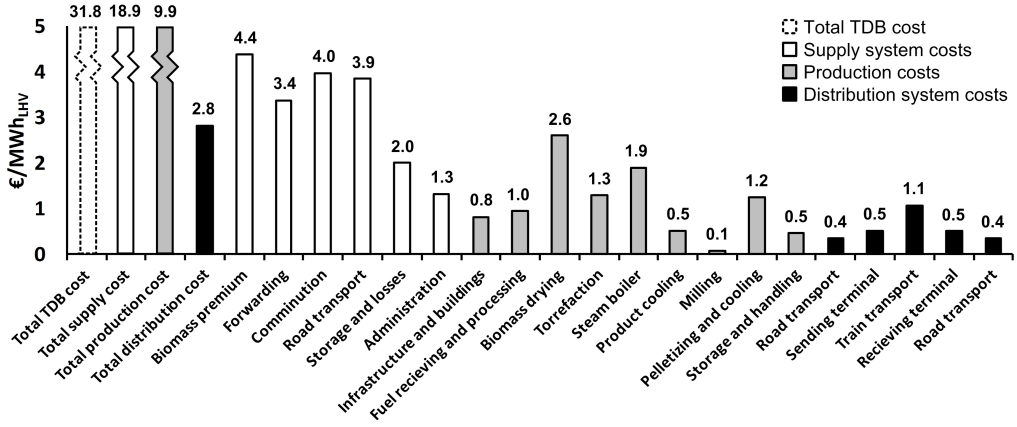

Figure 16: Costs for different activities

A vast number of parameters, both technical and logistical, were evaluated in a sensitivity analysis (see Table 6). The parameters with the highest impact were

amount of biomass, biomass premium, cost of forwarding, comminution and transport equipment, biomass moisture content, drying technology, torrefaction mass yield and pellet plant CAPEX. In relation, none of the factors within the distribution system had a large impact, e.g., increasing the rail distance by 50% only increases total cost by 1.7%. Hence, given that distribution of TDB accounts for such a small share of the cost and that train transport is not sensitive to distance, it is suggested that torrefaction plants should be located early in the supply chain.

Table 6: Sensitivity analysis of the most important variables affecting the supply, production, distribution and total product costs.

	Base case	**Unit**	**Parameter level/ change**	**Supp. cost**	**Prod. cost**	**Distr. cost**	**Total cost**
Supply system parameters							
Biomass moisture content	41.67	%	30 %	-4.6 %	-0.5 %	0.0 %	-2.9 %
			50 %	4.8 %	8.6 %	0.0 %	5.6 %
Amount of biomass	7.50	$ton_{DS}/km_2/yr$	+50 %	-3.3 %	-0.5 %	0.0 %	-2.1 %
			-50 %	7.5 %	1.0 %	0.0 %	4.8 %
Biomass premium	4.40	€/MWh_{LHV}	+25 %	5.8 %	0.8 %	0.0 %	3.7 %
			-25 %	-5.8 %	-0.8 %	0.0 %	-3.7 %
Logistics equipment	Separate comminution & transportation	unitless	Joint comminut. & transportation	10.2 %	1.4 %	0.0 %	6.5 %
Winding factor	1.34	unitless	1.42	1.1 %	0.1 %	0.0 %	0.7 %
			1.26	-1.1 %	-0.1 %	0.0 %	-0.7 %
Cost of road transports	3.86	€/MWh_{LHV}	+25 %	5.1 %	0.7 %	0.0 %	3.2 %
			-25 %	-5.1 %	-0.7 %	0.0 %	-3.2 %
Cost of forwarding	3.37	€/MWh_{LHV}	+25 %	5.9 %	0.8 %	0.0 %	3.8 %
			-25%	-5.9 %	-0.8 %	0.0 %	-3.8 %
Production configuration parameters							
Availability during operation	95	%	98 %	0.0 %	-2.3 %	0.0 %	-0.7 %
			92 %	0.0 %	0.8 %	0.0 %	0.2 %
Type of drier	Comb. HT-drier and LT-drier	unitless	HT-drier	0.3 %	7.9 %	0.0 %	2.6 %
			LT-drier	0.9 %	21.3 %	0.0 %	7.1 %
Torrefaction mass yield	77.0	%	87.2 %	-0.4 %	0.0 %	3.9 %	0.2 %
			66.8 %	1.3 %	20.3 %	-3.1 %	6.8 %
Power generation	No power generation	unitless	Power generation	0.2 %	4.4 %	0.0 %	1.5 %
Flue gas condensation	No flue gas condensation	unitless	Flue gas condensation	-0.1 %	-3.5 %	0.0 %	-1.1 %
Type of product storage	Outdoor storage on asphalt tile with side border	unitless	Indoor with border	0.0 %	2.4 %	0.0 %	0.8 %
			Outdoor no border	0.0 %	0.3 %	0.0 %	0.1 %
CAPEX/OPEX parameters							

Scale factor	0.70	unitless	0.80	0.0 %	-1.1 %	0.0 %	-0.3 %
			0.60	0.0 %	1.3 %	0.0 %	0.4 %
Change in price of electricity	56.6	€/MWh$_e$	+25 %	0.0 %	3.4 %	0.0 %	1.0 %
			-25 %	0.0 %	-3.4 %	0.0 %	-1.0 %
Cost of external services (1.0% of investment/ year)	0.455	M€/year	+50 %	0.0 %	2.2 %	0.0 %	0.7 %
			-50 %	0.0 %	-2.2 %	0.0 %	-0.7 %
Cost of personnel	1.7	M€/year	+25 %	0.0 %	4.2 %	0.0 %	1.3 %
			-25 %	0.0 %	-4.2 %	0.0 %	-1.3 %
CAPEX	45.5	M€	+25 %	0.0 %	14.1 %	0.0 %	4.4 %
			-25 %	0.0 %	-14.1 %	0.0 %	-4.4 %
Interest on capital	6.0	%	8.0 %	0.0 %	7.7 %	0.0 %	2.4 %
			4.0 %	0.0 %	-7.0 %	0.0 %	-2.2 %
License cost (0.5% of total sale/year)	0.16	M€/year	+100 %	0.0 %	1.5 %	0.0 %	0.5 %
			-100 %	0.0 %	-1.5 %	0.0 %	-0.5 %
Distribution system parameters							
Distance to terminal	5	km	+50 %	0.0 %	0.0 %	2.3 %	0.2 %
			-50 %	0.0 %	0.0 %	-2.3 %	-0.2 %
Total road transport	5+5	km	-100 %	0.0 %	0.0 %	-22.8 %	-2.2 %
Train distance	500	km	+50 %	0.0 %	0.0 %	18.1 %	1.7 %
			-50 %	0.0 %	0.0 %	-18.1 %	-1.7 %

The following variables were further analysed by modelling over the whole plant size span ranging from 25 to 500 kton$_{DS}$/year: amount of biomass, biomass premium, cost of forwarding, comminution and transport equipment, biomass moisture content, drying technology, torrefaction mass yield and pellet plant CAPEX. It was shown that the amount of biomass and type of transport vehicle had a major impact on the optimal size of plants. High amount of biomass and low cost of transport shifts the optimal size to larger plants. When transport cost increases and amount of biomass decreases, optimal size is achieved at a much smaller span compared (see Figure 17).

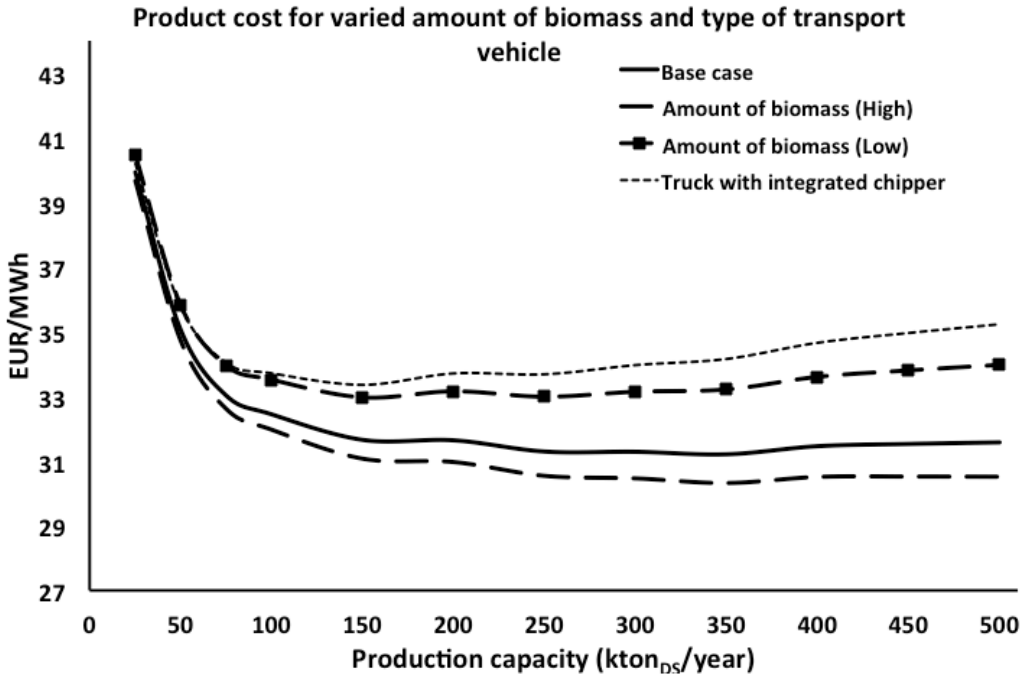

Figure 17: Optimal size of torrefaction plant for amount of biomass and type of transport vehicle

Contribution:

The primary contribution is to the industry and includes:

- The total cost of supplying TDB has been calculated and a number of central parameters affecting cost have been identified.
- Optimal sizes for torrefaction plants under different settings have been identified. Two variables, types of vehicles used (which render different transport costs) and amount of biomass have a large impact on optimal size of torrefaction plants.
- Given that distribution of TDB accounts for such a small share of total cost and is not sensitive to distance, it is proposed that torrefaction plants should be located early (close to the source of feedstock) in the supply chain.

5 Analysis

In this chapter, the findings in the papers are synthesised and analysed with respect to the research questions.

5.1 Biomass-to-energy supply chain configuration

As argued in the introduction and the frame of reference, an understanding of system components of biomass-to-energy supply chains in general, provides part of the foundation for future torrefaction configuration. For example, compared to other types of products such as consumables, biomass has a number of distinguishing product characteristics, such as being a low-density biological product, which must be taken into account when configuring the supply chain. Hence, the first research question aims at identifying characteristics of biomass-to-energy supply chains and was phrased as:
RQ1: What characterises the physical flow in biomass-to-energy supply chains?

The evidence for answering this research question is drawn from the first and the second papers. Data from interviews and the literature review provides support for the following argumentation. From paper I, the major finding contributing to answering the research question is the conceptualisation of important themes within biomass-to-energy supply chains. These were categorised according to *structure* and *operational performance*. From paper II, the contributions are the identified factors in terms of *external factors* and *efficiency factors*, which influence supply chain configuration. These overlap to some extent, and the terminology has changed slightly during the overall research process. This is the result of different methods (literature review versus interviews), different scope (biomass-to-energy in general versus forest residues) and different focus (SCM versus configuration of links, nodes and overall network structure). In order to synthesise and condense these findings, the term "characteristics" is used as a comprehensive term for describing the physical flow for biomass-to-energy supply chains. The scope in this section is primarily unrefined forest biomass. Characteristics can be seen as factors that influence supply chain configuration.

5.1.1 Characteristics of general biomass-to-energy supply chains

Perishability: Biomass is a perishable good, e.g., sensitive to time, and the supply chain must be configured to minimise losses in substance and quality.
Value and transportation properties: Biomass is a low-valued good with poor transportation properties (high bulk volume, low energy density, high moisture content). This makes transports costly and the economically feasible procurement area for a customer limited.
Connections to other supply chains: Biomass has a number of connections to other types of industries, products and supply chains. For example, forest residues for energy purposes and stemwood for pulp and paper purposes are separated from each other during harvesting, but can in subsequent supply chain steps benefit from interaction, e.g., using the same vehicles.
Fluctuations in demand: Energy production fluctuates both in the short and long-term due to weather seasons and fluctuating consumption, which has implications for procurement of biomass and the configuration of the supply

chain in terms of requirements on deploying buffers in the supply chain. Furthermore, the selection of vehicles must be done to deal with fluctuations in demand: depending on the length of the fuel season, vehicles might need to transport other types of goods in order to be profitable.

Gap between supply and demand: Due to a number of factors such as fluctuations in demand, connections to other supply chains, time constraints in the supply chain, customer preferences and accessibility of forest, there are a number of time-gaps between supply and demand, and the supply chain must be configured to bridge these.

Geographical spread: Biomass is scattered in small amounts over large regions. Given that customers are large, in single points, the supply chain must be configured and coordinated to manage converging flows.

Customer type: Customers (energy producers) of biomass are different with respect to a number of parameters such as type, size and location of plants, which have implications for supply chain configuration. Some customers require terminal supply whereas others can rely mostly on direct supply from roadside.

Weather and climate: Depending upon location, climate and weather can pose constraints on supply chain configuration, e.g., in terms of requirements of storage, vehicle selection or taking into account that waterways can freeze.

Relations between actors: Actors involved in the configuration of the supply chains need to be aware of other actors' and stakeholders' preferences which influence the decisions, e.g., in terms of basing decisions on environmental aspects instead of cost. Furthermore, links must be managed both vertically and horizontally in the supply chain. An example of this is the cooperation within procuring, which could result in minimised transport distances and hence reduced transport cost.

5.1.2 Frameworks for supply chain configuration

Most of the previously identified characteristics can be perceived as "problems" or "obstacles" that need to be addressed when configuring the supply chain in order to make biomass-to-energy cost competitive. Regarding configuration, there are a number of different decisions to make regarding location of nodes, function of nodes, where to perform operations, which vehicles to use within a link and overall network structure of the physical flow. This renders a large number of possible supply chain configurations. Given that it is not feasible to go through each configuration, three frameworks that facilitate achieving efficient and effective supply chain configuration are proposed instead.

Biomass-to-energy - the first mile problem: The specific transport cost is in general highest in the early stages in the supply chain, e.g., in the forest. Through consolidation of flows in nodes and through transhipment, e.g., switching from truck to train, the transport cost can be lowered. A node could be both a terminal, but also the roadside, as operations performed in terminals such as storing and processing can be done at roadside as well. By viewing the supply chain as a converging flow, this is a means to address the characteristic of *geographical spread*. The key decisions include location of nodes, and function of nodes (which is described further below) and routing, see (see Figure 18) for different examples. The high cost of initial transports and the issue of locating nodes to increase downstream transport efficiency justify the phrasing "the first

mile problem" as a research phenomenon and the network name: "the first mile network".

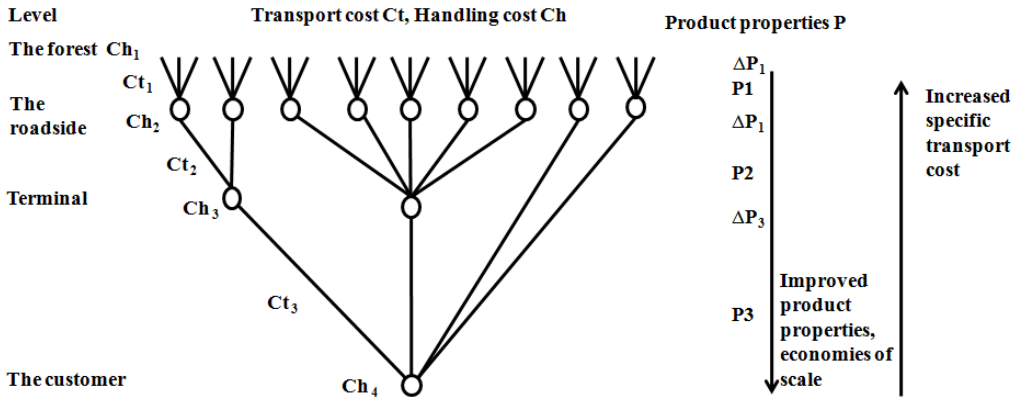

Figure 18: The first mile network

Node function: Nodes should be used to bridge different gaps that occur, in particular as storage in order to overcome *fluctuations in demand* and *connections* to other supply chains, and to bridge the *gap between supply and demand*. However, the node configuration needs to deal with the trade-off between storage efficiency and efficiency of logistics resources used for processing (comminution), in order to minimise the problems of *perishability*. This is an important issue as comminuted biomass is very sensitive to storage. Furthermore, through processing in nodes, the transportation and handling properties of biomass can be improved, which has positive effects on the subsequent transports and handling, addressing the problem of *low value and poor transportation properties*. In addition, nodes can be used to address the problem of low operational performance of transports by overcoming gaps in infrastructure, e.g., between in-forest transport and road transports, and between road transport and train transport. Hence, nodes are central parts in the physical flow, and the function of the node can be summarised as overcoming gaps between ingoing and outgoing flows in terms of frequency, time, capacity, product properties and infrastructure. This is an extension of a previously defined function of a node made by Hultén (1997); see Figure 19.

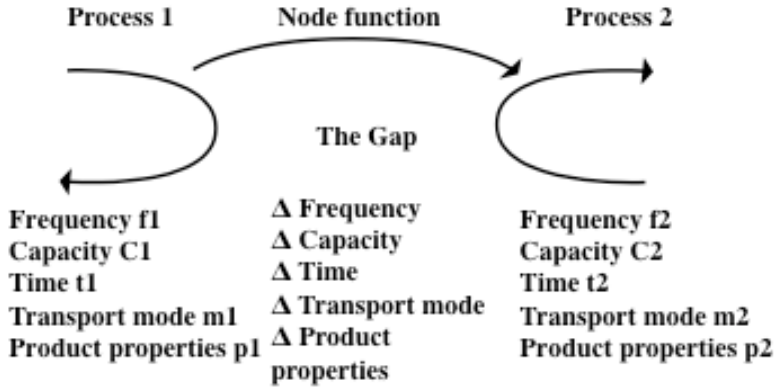

Figure 19: The function of the node, adapted from Hultén (1997)

Node interaction: Nodes can be made cost efficient through interaction with other types of product flows, e.g., in terms of sharing fixed and operating cost of terminals, the cost of biomass supply can be minimised. The same logic goes for links, e.g., some types of vehicles can be used to transport both forest fuel and stemwood for non-energy purposes. Thus, for logistics companies handling and transporting forest fuel, the supply chain cannot be seen in isolation, rather, the efficiency of the supply chain is highly dependent upon interaction with other types of flows; see Figure 20 for examples.

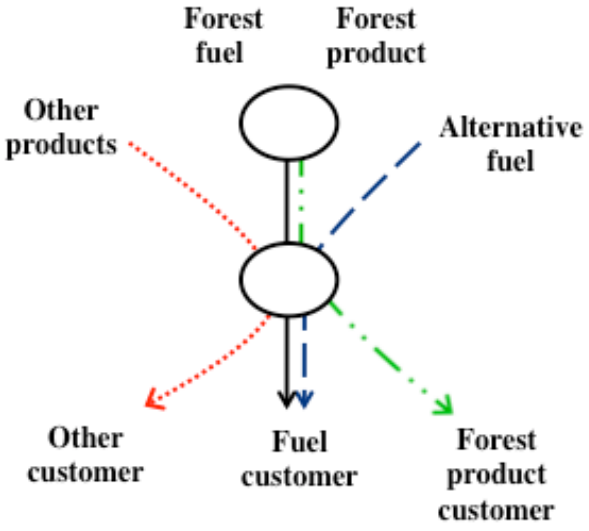

Figure 20: Interaction between biomass for energy and other product flows

5.2 Process technology in biomass-to-energy supply chains

Introducing a new process technology enables a number of new supply chain configurations. The second research question aimed at addressing how process technology that can be made use of different supply chains and was phrased as:
RQ2: What are the implications of a pre-treatment process on supply chain configuration?

5.2.1 Connection to findings in RQ1

The findings in RQ1 provide a part of the foundation for answering this research question. Out of the identified characteristics, it is primarily (1) *perishability* and (2) *value and transportation properties* that torrefaction will have a major effect on (see Table 7). How these logistical benefits will be made use of in different supply chains will be addressed in the next section. Regarding the identified factors that torrefaction will not have any primary effect on, these will rather serve as a checklist for different actors, of aspects that must be taken into account when configuring the torrefaction supply chain as well. For example, for supply to the torrefaction plant, it is likely that characteristics such as *weather and climate* will influence the selection of vehicles used for supply. Furthermore, another example is *relation between actors*, as cooperation within procuring could minimise transportation distance and hence transportation cost to the torrefaction plants. However, rather than going through all examples

again, which are thoroughly described in papers I and II, it is suggested that these characteristics (Table 7) serve as a checklist for different actors involved in torrefaction supply chain configuration. Even though these were empirically derived from supply chains for forest fuel, it is proposed that these comprise a checklist for characteristics for other biomass types as well. The same logic goes for the presented frameworks for supply chain configuration. For example, when introducing a torrefaction process into a forest residues supply chain, it is useful to address it as a first mile problem in order to achieve an effective and efficient supply chain configuration. A key issue is hence the location of the torrefaction plant and the function it will have in different supply chains.

Table 7: Torrefaction effect on characteristics

Torrefaction effect on:	**No primary torrefaction effect on:**
Perishability	Connections to other supply chains
Value and transportation properties	Geographical spread
	Customer type
	Weather and climate
	Relations between actors
	Gap between supply and demand
	Relations between actors

5.2.2 A framework for torrefaction configuration

As described earlier, the major benefit of a torrefaction process from a logistics perspective is the enhanced logistics properties that can be used to address characteristics in terms of (1) *perishability* and (2) *low value and poor transportation properties*. However, a vast number of types of feedstock are possible for torrefaction and there are potentially a number of different types of customers that can use TDB for energy production such as households and coal-fired power plants. Furthermore, there are a number of different decisions regarding upstream, torrefaction and downstream seen from the perspective of a torrefaction plant. This renders a number of different torrefaction configurations, which was addressed in paper III through the development of a framework for torrefaction configuration. The aim of the following section is to analyse the framework and describe how it can be used in different situations.

The framework is based on a number of attributes, which should be viewed on a continuum, where the purpose of the framework is to inform decision makers to find a niche for the torrefaction plant based on different types of demand. This approach is in line with Pagh and Cooper (1998), who suggest the use of profile analysis to decide the supply chain strategy. The essence of the framework is that the best fit is achieved if all attributes are chosen within the same column; in other words, a straight fit. As earlier argued, three types of distinct configurations for different demands (large coal-fired power plants, medium sized bioenergy plants and households) entail the framework. However, there are users of TDB that fall in between the three identified customer types; for example, medium sized power plants that produce base-load energy. Furthermore, there are other final applications for TDB than those discussed in the framework. Different types of vehicle fuel can be produced through gasification followed by a synthetisation process. These represent additional customer types, but the framework provides a viable starting point for

torrefaction configuration. Furthermore, there will be cases when a straight fit cannot be achieved due to opportunities, e.g., regarding feedstock. For these described customer types and cases, the framework should be used to identify "a straight fit", similar to the logic proposed by Pagh and Cooper (1998). Below, an example illustrates how the framework can be used.

There can be cases where there are regions with an abundance of by-products, e.g., from sawmills, compared to the local demand of TDB. Based on production economics, in terms of economies of scale, it is preferable to build a large torrefaction plant. However, this will result in production of an amount of TDB, which will be larger than the market that is economically viable to distribute to via truck. Hence, the supply chain needs to be configured to make use of this opportunity and the framework helps illustrate the trade-offs that must be made. One alternative is to reap advantages of economies of scale within the distribution system, using trains and ships to target industrial customers such as medium sized power plants. The resulting configuration can be seen in Figure 21. However, this configuration implies a trade-off in the sense that the optimal customers are not targeted, as a higher price can be charged from household customers due to the high quality of TDB using high quality by-products as feedstock. A second alternative (see continuous line, Figure 22) is to try to reach additional household customers. However, this results in long distance transport and possibly a number of transhipments. The torrefaction plant might need to be configured to produce TDB with high energy density in order to be efficient for transport, and high durability, in order to be resistant to handling losses that can otherwise occur during transhipment. Hence, the torrefaction plant has to deal with a potential trade-off between torrefaction cost, high energy density and high durability. Furthermore, compared to the previous configuration, the torrefaction has an additional function, to overcome gap in place, and there are thus trade-offs that the production strategy has to address (see dotted lines, Figure 22. Hence, it is concluded that the framework serve as a good starting point for torrefaction configuration in different cases, in which the aim is to identify that trade-offs that must be made, when deviating from the ideal, a straight fit.

Supply chain attributes		Type of customer		
		1. Large coal-fired powerplants	2. Medium sized bioenergy plants	3. Households
Demand	Quality	Low	↔	High
	Energy production pattern	Base-load	Fluctuating	Fluctuating
	Size of customer	Large	↔	Small
Torrefaction plant configuration	Location driver	Close to cheap feedstock	↔	Close to low cost production
	Plant Size	Large	↔	Small
	Function of process	Bridge gap in distance	Bridge gap in time	Bridge gaps in quality and ownership
Product characteristic	Main quality parameters	High energy density	Trade off between high energy density, durability and degree of hydrophobicity	Durability
Feedstock characteristic	Parameter affecting feedstock selection	Low cost	↔	High quality
	Feedstock competition and integration	Low	↔	High
	Feedstock location	Low cost country	↔	Close to market
Distribution system configuration	Inventory strategy	Minimise	Hold stock to bridge fluctuations	Hold stock for speculation
	Transportation mode	Large ships	Small ships, trains, trucks	Trucks
	Trading flexibility	Low	↔	High
	Network design	Physically efficient	Responsive	Responsive
	Lead time focus	Shorten as long as it doesn't increase cost	Invest to reduce lead-time	Invest to reduce lead-time

Figure 21: Framework for torrefaction configuration, example 1

Based on the previous examples and the findings in Paper III, the following two proposals are made:

- Depending on type of demand, torrefaction will serve several functions by bridging different types of 'gaps' in terms of time, place, time, quality and ownership.
- The production strategy of the torrefaction plant needs to be aligned with the distribution system according to the relative importance of different quality parameters (energy density, durability and hydrophobicity) that in

turn influence the supply chain efficiency for different types of customers.

Supply chain attributes		Type of customer		
		1. Large coal-fired powerplants	2. Medium sized bioenergy plants	3. Households
Demand	Quality	Low	⟷	High
	Energy production pattern	Base-load	Fluctuating	Fluctuating
	Size of customer	Large	⟷	Small
Torrefaction plant configuration	Location driver	Close to cheap feedstock	⟷	Close to low cost production
	Plant Size	Large	⟷	Small
	Function of process	Bridge gap in distance	Bridge gap in time	Bridge gaps in quality and ownership
Product characteristic	Main quality parameters	High energy density	Trade off between high energy density, durability and degree of hydrophobicity	Durability
Feedstock characteristic	Parameter affecting feedstock selection	Low cost	⟷	High quality
	Feedstock competition and integration	Low	⟷	High
	Feedstock location	Low cost country	⟷	Close to market
Distribution system configuration	Inventory strategy	Minimise	Hold stock to bridge fluctuations	Hold stock for speculation
	Transportation mode	Large ships	Small ships, trains, trucks	Trucks
	Trading flexibility	Low	⟷	High
	Network design	Physically efficient	Responsive	Responsive
	Lead time focus	Shorten as long as it doesn't increase cost	Invest to reduce lead-time	Invest to reduce lead-time

Figure 22: Framework for torrefaction configuration, example 2

It is acknowledged that this framework is a proposition based on the current state of the research field. However, the major contribution is not the entailed configurations for the three identified customers, but rather the framework itself. There are a number of "black holes" within the scientific community regarding torrefaction research, in particular between different quality parameters and cost,

and handling properties. Future research may find ways to develop a torrefaction process that excels on all quality parameters with a viable torrefaction cost. There might also be other game-changers, such as legislation or technological development, e.g. heavier vehicles that can utilise the full potential for TDB from a weight perspective, which makes the feasible distribution radius longer, and might require another torrefaction configuration that favours energy density as a quality parameter. This development could hence result in an altered framework. However, at the current state of research, the framework is proposed as a good starting point for torrefaction configuration.

Finally, to sum up the findings, it is fruitful to illustrate the torrefaction process in a supply chain perspective by making a comparison with the role of a distributor in a distribution network (see, e.g., Jonsson (2008) and reconnecting to the identified barriers regarding movement of energy, identified in chapter 1. For torrefaction configuration, the following is proposed:

- The torrefaction process can create form utility, which can be used to overcome the gap between low quality of feedstock and demand of high quality from customers.
- The torrefaction process can create time utility through excellent storage properties of TDB, which can be used to overcome the gap between fluctuating supply and demand.
- The torrefaction process can create place utility through excellent transport properties of TDB, which can be used to access the unutilised potential of biomass.

5.3 Relation between torrefaction configuration and supply chain performance

In order for torrefaction supply chains to be efficient, operators of torrefaction plants need to understand how different decisions at the torrefaction plant affect the supply chain performance, in terms of supply chain cost. The third research question was phrased as:

RQ3: How does torrefaction configuration relate to supply chain performance?

Paper IV addressed how different parameters affect supply chain cost. However, due to journal requirements on length and paper structure, it was not thoroughly shown and explained how these are related, focus was rather on providing comprehensive numerical results. Furthermore, the numerical results in paper IV are only valid within the studied case (the modelled supply chain under Swedish conditions), with the exception of the sensitivity analysis, which points in a direction for other cases as well. Hence, in order to contribute to torrefaction configuration in other cases, a framework that analyses and visualises the findings in is presented below.

Paper IV has a number of connections to papers I-III and the findings of previous research questions. Paper IV is connected to paper III in the sense that the supply chain evaluated entailed the framework proposed in paper III (medium-sized CHP). Furthermore, in paper IV, effects on changes in cost were evaluated as a function of variations in parameters, of which some are attributes from paper III and some are variations in characteristics, which were identified

in papers I and II, answering RQ1. The rest of the parameters were drawn from the literature or emerged during model development.

In order to show how torrefaction configuration relates to supply chain performance, a framework, consisting of a conceptual model (see Figure 23 for the model, and examples in Figures 24, 25, and 26) and two empirically supported tables (see tables 8 and 9) is proposed. In the model, the continuous lines represent empirically observed effects, and the dotted lines represent effects, which are conceptually argued for or drawn from the literature.

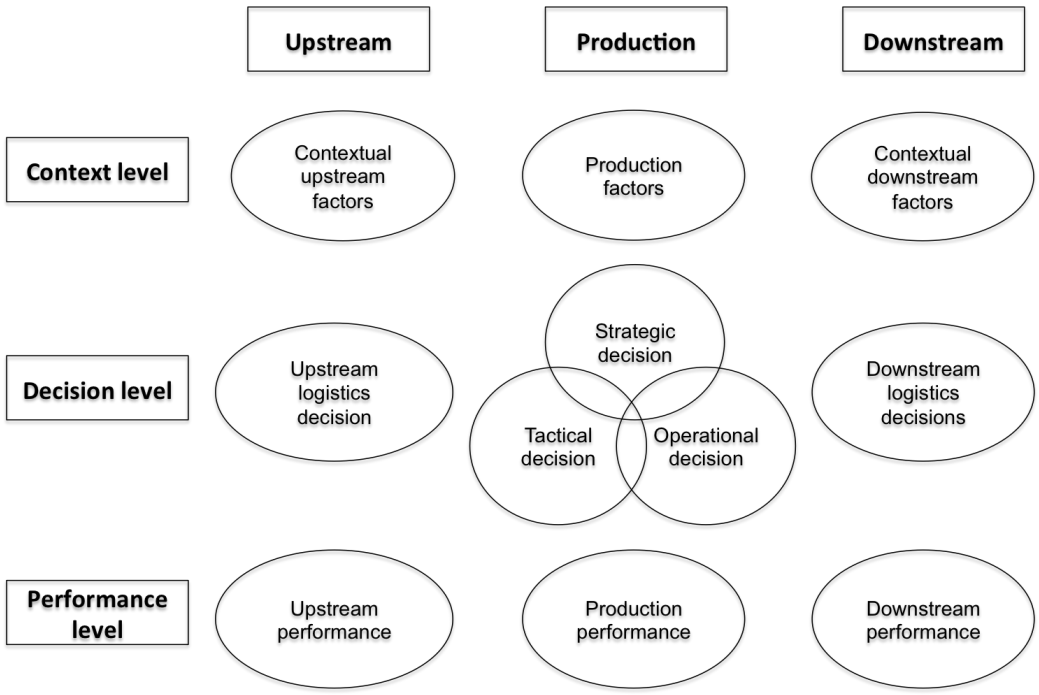

Figure 23: A framework showing relations between torrefaction configuration and supply chain performance

The supply chain is divided into three stages, where upstream refers to activities involved in procuring feedstock for torrefaction, production refers to the transformation of unrefined biomass to TDB and downstream refers to the activities involved in distribution of TDB to end-users. Three different levels are also proposed, which comprise the context level, the decision level and the performance level. The context level and decision level comprises what is phrased in paper IV as parameters. The context level describes the environment, e.g., the amount of biomass available within a certain region. The decisions level describes the decisions that can be made, e.g., which types of technological decisions to make or which logistics resources to use for handling and transportation. The third level describes the performance, in this case addressed through cost. The main reason for discussing in terms of performance and not only in terms of cost is that there is a strong relation between cost and other measures such as CO_2-emissions or energy consumption in the torrefaction supply chain. For example, increasing the production volumes of a torrefaction plant implies a larger procurement area, which results in both higher costs and higher energy consumption within transportation due to longer transportation distance. However, the relation between cost, energy and CO_2 is not explored in

detail, but rather, it is proposed that the framework could be useful to address these relationships, but quantification is left as an area of future research. Furthermore, supply chain performance goes beyond cost, CO_2-emissions and energy consumption, e.g., Gunasekaran et al. (2004) developed a framework for supply chain performance measures with emphasis on suppliers, delivery performance, customer-service, and inventory and logistics cost. However, these measurements require another framework than the model presented here, which is an area for future research.

The stages and the levels in the model form a 3*3 matrix where the purpose of the model is to illustrate relations between decisions on different time horizons (strategic, tactical and operational) and performance (upstream, production and downstream). Hence, when using the model, the starting point is making decisions regarding torrefaction, and the arrows show effects on different parts and levels in the supply chain. Below, three examples, empirically supported from paper IV, are used in order to illustrate a number of important relations observed.

5.3.1 Operational decisions

Operational decisions are made in the short term, e.g., on a daily basis. From modelling of the torrefaction supply chain, one of the most important decisions identified was regarding product properties, in terms of energy density, which can be controlled through altering mass yield. Requirements on product properties can be dependent upon distance to a specific customer, and can hence be desirable to alter on short-term notice, e.g., when switching customers. It was shown that decisions on product properties affect production performance, as well as upstream and downstream performance; see continuous lines, Figure 24. First of all, decisions on product properties affect production performance, as it costs more to attain better product properties, given that more biomass is required for drying in the torrefaction plant. In the supply chain in paper IV, the cost increase, due to altered product properties, was 20.3%. Secondly, due to enhanced transportation properties, the downstream performance is improved; in this case an effect of 3.1% was observed. Thirdly, altered product properties have upstream effects as well. The increased amount of required biomass implies a larger procurement area, which implies a longer average driving distance for trucks, which results in a cost increase of 1.3% and a decreased upstream performance. This in turn has negative effects on the production performance as well. This is due to the fact that more has been paid for the biomass supplied to the torrefaction plant and some of the produced TDB is used to fuel the torrefaction process itself. Hence, altering product properties has effects on upstream performance, which in this case affects the production performance as well. The total effect of altering product properties resulted in an increase in cost of 6.8%, and hence a decrease in performance.

The combination of altering product properties and type of supply trucks was not modelled simultaneously, but it was shown in a separate analysis that different trucks have different performances for different transportation distances (see dotted lines, Figure 24, which also is well known within biomass-to-energy literature; see, e.g., (Ranta and Rinne, 2006, Johansson et al., 2006). This implies that there will be cases when increased cost resulting from altering

product properties to some extent could be minimised by making logistics decisions in terms of switching the types of transport truck. Furthermore, choosing transport mode and type of vehicle according to product parameters, e.g. in terms of adapting to weight restrictions, could further improve the enhanced downstream performance, which is a result of enhanced product properties. Hence, to sum up, an operational decision such as improving product properties has effects both on production and on upstream and downstream performance. However, there is the possibility to limit the negative impact or enhance the positive impact on performance by making different upstream and downstream logistics decisions.

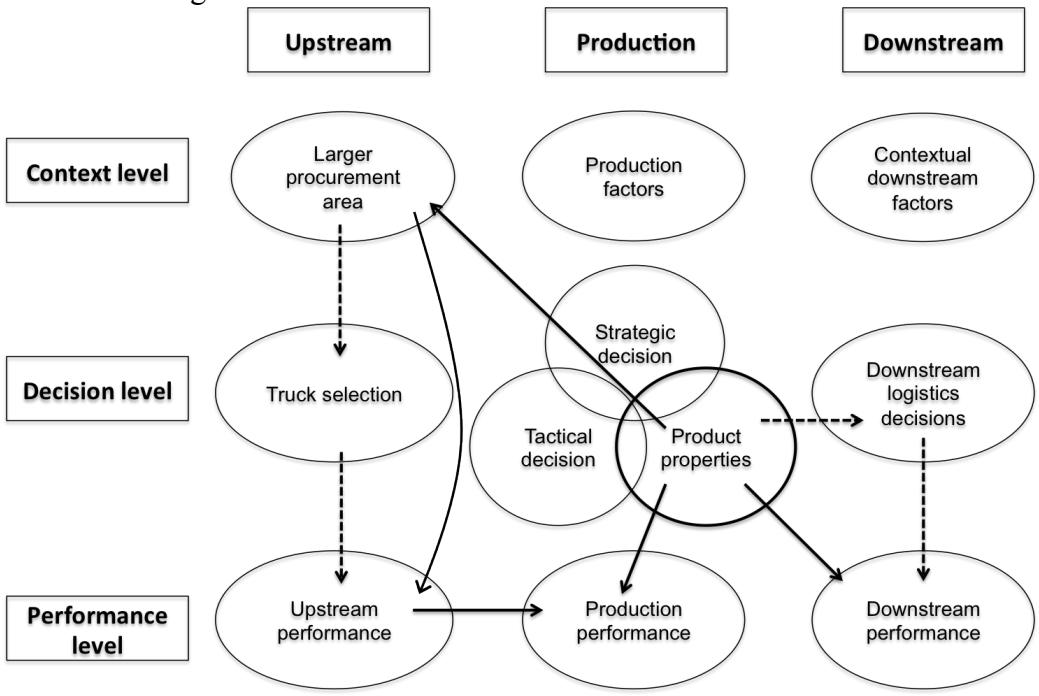

Figure 24: Effects due to altered product properties

5.3.2 Tactical decisions

Tactical decisions are made on medium time horizons. One important decision identified is procurement of biomass. Biomass varies in quality, e.g., in terms of moisture content, which is due to type of biomass, regional differences and whether covered roadside storage has been applied or not. Hence, there are different means to attaining biomass with different quality. In general, it is often argued that biomass with low moisture content is beneficial, but below a certain level (39% in the modelled case), the modelling showed that there either has to be a heat sink in terms of district heating, or the mass yield (an operational decision) has to be increased to reduce the torrefaction gas flow, i.e., to make use of the excess heat produced. In other words, there is a relation between decisions made at different time horizons, e.g., locating a torrefaction plant without integration to district heating (a strategic decision) reduces the possibility to make use of biomass with lower moisture content. In the modeled case, without integration to district heating, lowering the moisture content only had minor positive effects, resulting in a cost reduction of -0,5% compared to increasing the moisture content, which resulted in a cost increase of 8,6%. Thus, it has been shown that tactical decisions are dependent on strategic decisions as well as operational decisions; see double-sided arrows, see Figure 25.

Furthermore, altering moisture content to higher and lower levels resulted in altered transport cost to the torrefaction plant of -4,6% and +4,8%, which resulted in the same effects on performance with the similar logic as in the previous example.

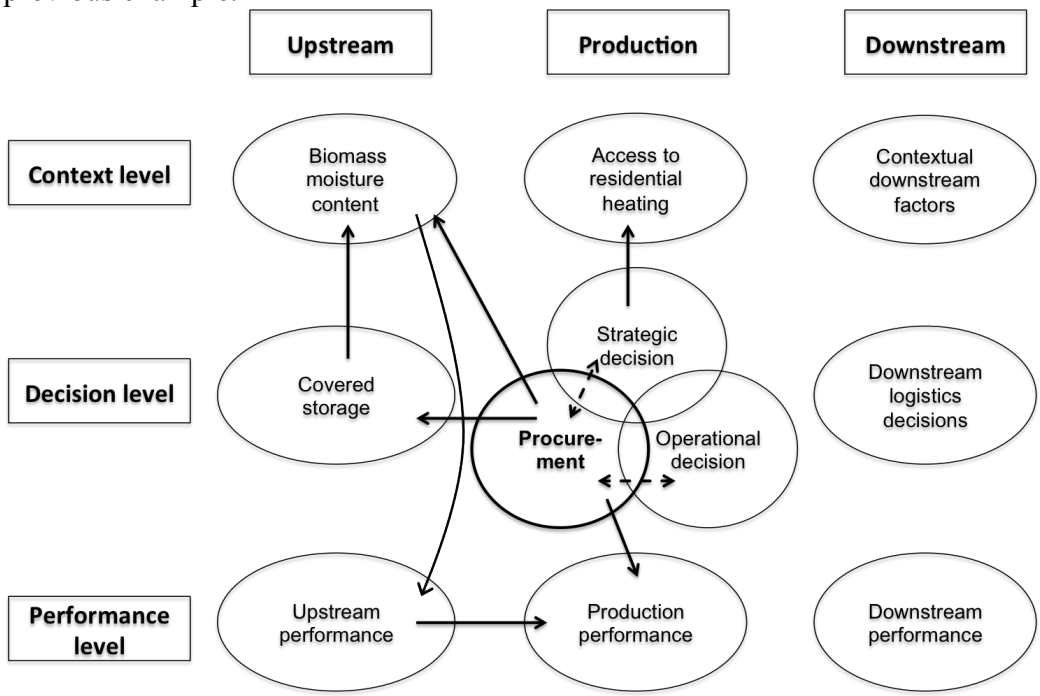

Figure 25: Effects of procurement strategy

5.3.3 Strategic decisions

An important strategic decision, which is taken on long term, is the location of the torrefaction plant; see Figure 26. One of the primary effects on upstream context is a regional feedstock characteristic, in terms of available amounts of biomass, which is a function of regional yield and competition. It was shown within modelling that the amount of biomass has large effects, both on the strategic decision of size of the plant and on production and upstream performance. The amount of biomass has effects on the average driving distance, which affects upstream performance, which in turn affects production performance. Furthermore, location has effects on a number of contextual production factors, such as integration, both in terms of utilising high valued excess heat from industries which could reduce torrefaction cost, but also, as previously described, releasing low valued heat to residential heating. This in turn has effects on production performance, in line with the literature, where it has been shown that conventional pellet plant integration with CHP is energy efficient (Song et al., 2011).

The effect of distance between location and customer was not modelled using any geographical information system, but simple logic implies that location affects distance to customer. Furthermore, it has been noted that some pellet plants are land-locked (van Dam et al., 2009), which hence affects decisions on which vehicle or transport mode to use to supply plants. Thus, location ought to have an effect on downstream performance as well.

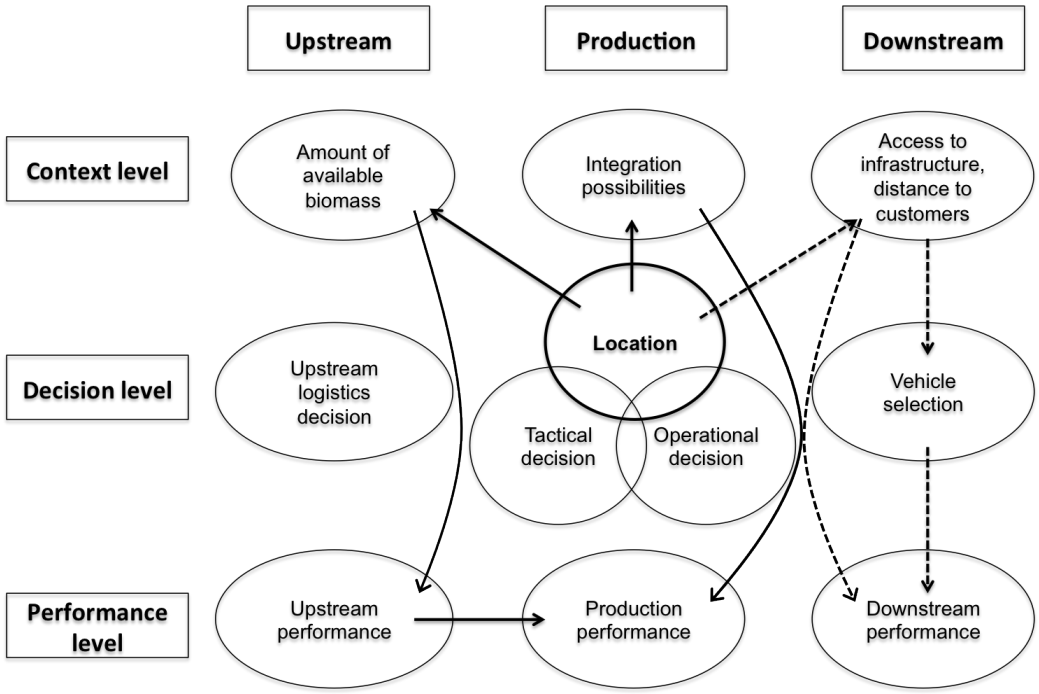

Figure 26: Effects of altering location

5.3.4 Further analysis in different cases

The developed model can be used for future modelling to identify and illustrate relations between context, decisions and performance. As a support for such evaluations, the findings in paper four are categorised in Table 8.

Table 8: Findings from techno-economical modeling

	Upstream factors	Production factors	Downstream factors
Context level	• Biomass moisture content • Amount of available biomass • Biomass premium • Winding factor • Cost of logistics equipment	• Price of electricity • Cost of personnel • CAPEX • Interest on capital • License cost	• Terminal location • Distance to terminal • Distance to customer
Decision level	• Logistics equipment decisions	• Size • Location • Availability • Selection of drying technology • Torrefaction mass yield • Power generation • Flue gas condensation • Type of product storage	• Torrefaction plant location (in relation to terminal)

In addition, findings from a literature review identify a number of factors from different biomass-to-energy supply chains, and bulk cargo supply chains which could be evaluated in future modelling of torrefaction supply chains (see Table 9). These should be seen as a compliment to the findings in paper IV, and comprises factors and decisions that were not evaluated in paper IV due to reasons such as delimitations in scope of the model, e.g., some transport modes were not included, such as sea or ocean shipping. Together, the model and the two tables constitute a framework that can be used as an approach to identify important relations between torrefaction configuration and performance. However, the proposed framework could also be used as starting point for evaluation of the relation between other types of pre-treatment processes and performance as well.

Table 9: Findings from literature review

	Upstream factors	Production factors	Downstream factors
Context level	**Forwarding:** • Forest geography **Comminution:** • Operators • Local environment • Weather • Harvesting conditions • Roadside landing capacities **Road transport:** • Biomass properties • Distance • Road properties • Infrastructure • Possibility of backhaul **Storage:** • Time • Volume	• Integration possibilities	• Infrastructure
Decision level	**General:** • Selection of equipment • Shape of biomass • Bartering volumes **Comminution:** • Location of comminution • Volumes • Assortments decisions • Organisational setup **Storage:** • Layout	• Scope of customers	• Scale and scope of terminals • Open or closed terminals • Structure of transportation network • Scheduling of trains

Hence, from this conceptual framework, which was based on techno-economic modelling and literature, the following can be concluded with regard to RQ3:

- The model provided a useful approach for illustrating relations between the different stages of the supply chains, in terms of upstream, production and downstream, and different levels in terms of context, decisions and performance. This was exemplified and empirically supported from paper IV to show a number of relations for operational, tactical and strategic decisions.

In particular, the following important relations were observed:

- Decisions within a torrefaction plant can have effects both on upstream, production and downstream performance.
- There are relations between strategic, tactical and operational decisions in a torrefaction plant.
- Decision on production configuration affects upstream performance, which has implications for production performance.
- There is a possibility to minimise the negative performance or enhance the positive performance that is a result of torrefaction decisions by making upstream and downstream logistics decisions.

Finally, with regard to the conceptual framework behind this thesis the following is justified:

- Early in this thesis it was stated that it is important to have a systems approach. This has been validated as multiple relations between decisions and performance in different stages in the supply chain have been shown.

5.4 A summary of the research process

Finally, a summary of how the research questions were addressed can be seen in Table 10.

Table 10: A summary of how research questions have been addressed

RQ	Literature	Empirical evidence	Papers	Results
RQ1:	A number of themes regarding structure and operational performance of biomass-to-energy supply chains were identified. A literature review identified factors influencing supply chain configuration.	Interviews with actors within industry complemented the current body of knowledge regarding factors influencing supply chain configuration.	P1 and P2	The literature and empirical evidence was synthesised as characteristics influencing the biomass-to-energy supply chain in the kappa. Furthermore, three frameworks for supply chain configuration were presented.
RQ2	A literature review identified attributes of torrefaction supply chains, which were conceptualised a framework.	None	P3	A framework for torrefaction configuration was proposed, with three types of distinct customers entailing the proposed framework. The framework was further explained in the kappa.
RQ3	A literature review provided a foundation for model construction and further evaluation.	Techno-economic modelling provided empirical support for framework development.	P4	In the kappa, a framework was proposed, describing how torrefaction configuration relates to supply chain performance

6 Conclusions, contributions and future research

In this chapter, the conclusions of the thesis are presented. Furthermore, contributions with regard to three different groups: industry, the bioenergy community and the logistics community are presented. This is followed by a short remark on the use of terminology throughout the thesis. Finally, directions for future research are outlined.

6.1 Conclusions

A number of characteristics of the physical flow in biomass-to-energy supply chains were identified through literature reviews and interviews:

- **Perishability**
- **Value and transportation properties**
- **Connections to other supply chains**
- **Fluctuations in demand**
- **Gap between supply and demand**
- **Geographical spread**
- **Customer types**
- **Weather and climate**
- **Relations between actors**

These characteristics basically serve as a checklist for different actors involved in supply chain configuration, e.g. as different aspects that need to be taken into account. Based on these characteristics, three frameworks to achieve effective and efficient supply chain configurations were proposed:

- **The first mile network** – describing the overall network structure
- **The node function** – describing how nodes should be used
- **Interaction with other product flows** – describing how to achieve efficient nodes and links through interaction with other product flows

These characteristics were identified in biomass-to-energy supply chains without torrefaction processes. However, it was argued that these could serve as a checklist for actors involved in future configuration of torrefaction supply chains as well.

In order to further address how torrefaction can be configured in different supply chains, a framework for torrefaction configuration was developed. This was based on a number of literature-derived attributes, describing what differs between supply chains. Based on different demand types, three types of supply chains entailed the framework, but it was argued that the major contribution is the framework itself. Furthermore, two propositions were derived:

- Depending on type of demand, torrefaction could serve several functions by bridging different types of ‘gaps’ in terms of time, place, quality and ownership.
- The production strategy of the torrefaction plant needs to be aligned with the distribution system according to the relative importance of different quality parameters (energy density, durability and hydrophobicity) that in turn influence the supply chain efficiency for different types of customers.

One of the supply chains, which entailed the framework, was selected for quantitative techno-economic analysis. A system model was developed to analyse the performance of a feasible torrefaction supply chain under Swedish conditions. It was shown that the optimal size of the torrefaction plant is in the range of 150-200kton/year. It was also shown that distribution of TDB is cost efficient in comparison to other system parts and activities in the supply chain, which implies that a torrefaction plant should be located early in the supply chain. Furthermore, a number of parameters affecting the performance of the supply chain and the size of the plant were identified.

In order to provide support for analysis in other cases regarding how torrefaction configuration and performance are related, a framework was proposed. This consist of a model and two tables, into which the findings from paper IV and a literature review were categorised. The model was based on a division into different stages of the supply chain: upstream, production and downstream and how these relate to three levels: the context level, the decision level and the performance level. Four conclusions were drawn from the empirically supported framework:

- Decisions within a torrefaction plant have effects both on upstream, production and downstream performance.
- There are relations between strategic, tactical and operational decisions in a torrefaction plant.
- There is a possibility to minimise the negative performance or enhance the positive performance that is a result of torrefaction decisions by making upstream and downstream logistics decisions
- Decision on production configuration that affects upstream performance has implications for production performance as well.

Hence, to sum up, the purpose of this thesis has been addressed by the development of several frameworks. Firstly, general biomass-to-energy supply chains without torrefaction processes were reviewed. The findings were classified into characteristics of the physical flow and further refined into three minor frameworks for supply chain configuration. Secondly a framework torrefaction configuration was developed and analysed in the kappa. Finally, yet another framework has been developed, which describes the relation between torrefaction configuration and supply chain performance.

6.2 Contributions

There are contributions of the thesis that are of interest for three different groups: (1) industry, (2) the bioenergy research community, and (3) logistics and SCM research communities. This section presents the contributions with respect to each group and is structured around the papers and the kappa. A summary can be seen in Table 11.

The primary audience of the first paper was the SCM research community, for which the identified trajectories provide direction for future research on the intersection between energy and SCM. However, as argued in the frame of reference, the use of the phrase *supply chain design* can have various meanings. For the bioenergy community, supply chain design has been addressed in terms

of optimisation of the physical flow, e.g., on aspects such as vehicle selection or terminal location. By comparison, supply chain design has a much wider meaning for the SCM research community. The contribution to the bioenergy community is the conceptualisation of central themes within energy supply chains that could serve as an eye-opener for bioenergy researchers to a wider understanding than the physical flow, e.g., managing the supply chain through different relations in terms of links to vertical and horizontal companies.

The contributions from the second paper are: (1) the vast set of factors influencing the configuration of biomass-to-energy supply chains, and (2) three minor frameworks for supply chain configuration. For the bioenergy community, the main contribution is the identified factors providing directions for future research, but also serving as a starting point for making clear delimitations of what has been disregarded or can be incorporated into optimisation models. For the industry, there are primarily two contributions. Firstly, the three identified frameworks provide a good starting point for understanding how to achieve an effective and efficient supply chain. Secondly, the factors provide an overview for actors within biomass-to-energy supply chains that can be used as a starting point for different actors to understand each others' operations and to avoid supply chain sub optimisation. For the logistics research community, the main contribution is the three identified frameworks, which could be interesting to evaluate for other types of bulk goods, e.g., other types of perishables such as fruit.

From the third paper, the contribution to the industry is the framework, which provides an understanding for how torrefaction supply chains could be configured. For the bioenergy research community, the contribution is the framework itself, the entailed configurations, and paths for future research. Furthermore, the proposed framework could very well be of interest for evaluation of other pre-treatment processes such as steam explosion or pyrolysis. As a comparison, pyrolysis is a liquid, which hence requires other handling systems, but the identified attributes in the framework and the approach presented could be used as a starting point for refining of the framework to suit configuration of these processes as well. For the SCM community, the paper has made a minor contribution to supply chain design. The framework was been developed in a biomass-to-energy context, but could provide insight for configuration of process technology for other types of goods as well.

The contribution from the fourth paper is primarily to the industry. Through taking a systems perspective, proposals on optimal size of torrefaction plants have been made and important parameters affecting total supply chain cost and plant size have been identified. This provides good support for actors involved in constructing and operating torrefaction plants. The findings in the paper are of minor, but similar interest to the bioenergy research community for further research.

The kappa analysed the findings with respect to the research questions. In addition, a framework was presented aimed at addressing how torrefaction configuration relates to supply chain performance. For the industry, this provides an understanding for how different decisions affect the performance of

the supply chain in terms of cost. For the bioenergy research community, this provides a useful framework for explaining relations and not simply stating costs. Previous research on biomass-to-energy often addresses both decisions and contextual parameters as the same thing without much afterthought. Furthermore, the framework ought to be valid for configuration of other pre-treatment processes as well, but with different impacts on performance of the identified decisions and factors.

Table 11: Contribution from each paper and the kappa

	The industry	Bioenergy research community	SCM/logistics communities
Paper I	Trajectories for energy management	A wider meaning of supply chain perspective than the mere physical flow.	A conceptualisation of central themes provides three trajectories for future research that SCM-researchers ought to address.
Paper II	A vast set of factors influencing biomass-to-energy supply chain configuration that provide an understanding for different actors to understand each others' decisions. Three perspectives that serve as a starting point for torrefaction configuration	A vast set of factors that can be incorporated into or used to make clear delimitations of optimisation models. A number of directions for future research.	Three perspectives that could be interesting to evaluate for other types of bulk commodities, e.g., perishables.
Paper III	A framework that can inform decision makers of biomass-to-energy supply chain, in particular operators of torrefaction plants about the upstream and downstream implications of their decisions.	The framework provides direction for different types of research.	The paper itself provides an approach for how to address the implementation of a new process technology and the effects this has on supply chain configuration. Configuration for three customers entailed the framework.
Paper IV	Identification of parameters affecting torrefaction supply chain cost and torrefaction plant size.	Identification of parameters affecting torrefaction supply chain cost and torrefaction plant size.	
Kappa	A framework for how torrefaction configuration relates to supply chain performance.	A framework for how torrefaction configuration relates to supply chain performance.	

6.3 Comments on terminology throughout the thesis

Upon finishing this thesis, a number of issues regarding use of terminology have been identified that are worth commenting on. First of all, the term *configuration* has been used frequently in this thesis, both as a noun to describe the result (a specific configuration), but also as a verb to describe how to achieve the result; in other words, the process of configuring the supply chain. Furthermore, the phrasing configuration comprises both a technical dimension in terms of decisions of how a torrefaction plant is constructed (e.g., technology selection), and a supply chain dimension in terms of different decisions regarding the supply chain. When continuing research on torrefaction, introducing more distinct terms would make the results clearer, e.g., using configuration to describe upstream and downstream decisions (regarding the supply chain) and describing decisions in the torrefaction plant with the phrasing "technological set-up" instead.

Furthermore, the definitions of characteristics, attributes, parameters and contextual factors are not always clear-cut. Some aspects are hard to classify, or in other words pinpoint what they really "are". For example, it was argued that poor transportation properties is a characteristic of the physical flow of biomass. However, the transportation properties are a function of the moisture content of biomass, which in paper IV was presented as a parameter that can vary, depending on location and roadside drying. Thus, when comparing characteristics, attributes, parameters and contextual factors, some confusion could arise as they to some extent overlap. However, separating them is still perceived as the better option, as treating them as one group would make understanding of the results harder to grasp.

6.4 Future research

In this thesis, it was only paper I that had a SCM perspective. The three following papers were narrower, focusing mainly on the physical flow of biomass. A possible future research path is to take a SCM perspective on the torrefaction process. For example, in paper I, it was identified that CHP uses a number of different sources of biomass, which requires management of vertical and horizontal links with other actors. It was concluded that principles of SCM have a strong potential to address these structural elements, as a key foundation within SCM is relationship management. Torrefaction plants may as well use a number of sources of biomass and will hence have to manage both vertical as well as horizontal links, which justifies the attention of SCM researchers.

Paper IV addressed economics of a torrefaction supply chain in a national perspective. As a follow-up to this, three paths for further research are proposed. Firstly, given that one simplification in the paper was a one-to-one perspective, without competition and overlapping of procurement areas for the plants, a future research path could be to use geographical information systems (GIS) and optimisation models to evaluate the findings. Secondly, the unutilised potential of biomass in Sweden is low in an international perspective, e.g., compared to Brazil, Canada, Russia and parts of Africa. Future research should address the

configuration of these supply chains, e.g., with respect to size and location of torrefaction plants. Thirdly, an interesting research problem from a supply chain perspective is the alignment of the design of the shipping system and the production strategy, e.g., which product quality is required for different supply chains.

In paper III, a number of research gaps were identified and it was concluded that future research needs to address issues of production cost, product quality, performing empirical tests of handling and transportation, and assessing different customer requirements on quality and service level. Once these have been assessed it is possible to further develop and refine the strategies for torrefaction configuration. For example, assessing the cost of producing TDB with excellent storage properties is essential in order to deploy shipping strategies that exploit the fluctuating ocean shipping rates.

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APPENDIX A

Frågor till kunder av skogsbränsle

Bakgrundsinformation om den som intervjuas

1. Vem är du (befattning + bakgrund)?
2. Vilka bränslen köper du in?

Om anläggningen och användning av bränsle

3. Vad är det för typ av anläggning bränslena används i?
4. Hur ser er värme respektive el produktionen ut över året?
5. Vilka typer av bränslen används i anläggningen?
6. Vilken flexibilitet har ni i att byta mellan olika bränslen?
7. Hur ser användningen av GROT ut under året?
8. Hur ser användningen av andra typer av skogsbränslen ut under året?

Om bränslekvalitet

9. Vilka kvalitetskrav har ni?
10. Hur påverkar era kvalitetskrav försörjningskedjan i föregående led?
11. Är kvalitet ett krav ni tydligt kommunicerar med era leverantörer?
12. Hur ser ni på grön kontra brun grot?

Om transportsystem

13. Hur långa är transportavstånden?
14. Vilka transportsystem används för att leverera respektive bränsle?
15. Hur ser transportvägen från skogen till anläggningen med avseende på mellanlagring i t.ex. terminaler?
16. Vilka faktorer är avgörande för att transportvägen ser ut som den gör?
17. När och varför används respektive transportsystem?
18. Om tåg respektive båt används, vad är anledningen till detta?
19. Hur långt är det till närmaste tågspår respektive hamn?
20. Vad har påverkat val av transportlösning?

Om egna terminaler

21. Levereras bränslet via egen terminal och i så fall varför?
22. Är ni intresserade av att ha en egen terminal i nära anslutning till er anläggning?
23. Vad ser ni för fördelar respektive nackdelar med en egen terminal?

Om lagring och sönderdelning

24. Hur stora lagringsmöjligheter har ni?
25. Hur påverkar era lagringsmöjligheter försörjningskedjan?
26. Har ni möjlighet till att sönderdela grot eller annat skogsbränsle själva?
27. Hur påverkar era möjligheter till sönderdelning försörjningskedjan?
28. Vilka faktorer styr dimensionering av lager?

Om leverantörer och leverensservice

29. Vilka faktorer är avgörande när ni väljer leverantörer?

30. Vilka krav har ni på leverensprecision, leveranssäkerhet samt leverensflexibilitet?
31. Hur påverkar era krav på leverensservice försörjningskedjan
32. Uppstår bristsituationer/Vad händer vid bristsituationer?
33. Med vilken framförhållning beställs volymer?
34. Vilken flexibilitet finns i det mängd skogsbränsle som en leverantör kan leverera?
35. Hur löses fluktuationer i efterfrågan (både på kort och lång sikt?)
36. Hur påverkar väderfluktuationer försörjningen?

Övrigt

37. Har ni några planer på att byta skogsbränsle med andra leverantörer om det är mer lönsamt ur transportsynpunkt?
38. Vad anser du vara viktigt för en väl fungerande logistik för GROT och annat skogsbränsle?

Frågor till producenter av skogsbränsle

Bakgrundsinformation om den som intervjuas

1. Vem är du? (befattning plus bakgrund)

Information om företaget och dess kunder

2. Hur ser er företagskonstruktion ut (äger ni skog själva eller vilken typ av producent är ni)?
3. Vilka typer av bränsle säljer ni?
4. Till hur många olika kunder levererar ni, samt till vilka typer av kunder levererar ni?
5. Hur förändras volymer från år till år som ni levererar till kunder?
6. Hur förändras produktionen av GROT respektive andra skogsbränsle från år till år?
7. Vilka faktorer styr hur mycket GROT och skogsbränsle ni skall producera/som produceras?
8. Hur ser ni på brun kontra grön GROT?

Om transporter och transportsystem

9. Vilka metoder används för att transportera (skota) GROT) respektive andra trädbränslen i skogen?
10. Vilka faktorer har varit avgörande för val av hur GROT respektive andra trädbränslen transporteras i skogen?
11. Vilka delar i försörjningskedjan sköter ni själva respektive gör entreprenörer? (B)
12. Vilka typer av fordon använder ni för transport?
13. Vilka faktorer styr vilka typer av transportslag respektive typ av fordon som ni använder er av?
14. Är schemaläggning av entreprenörer ett problem?
15. Finns det ett tydligt systemtänk med avseende på logistikupplägget för hela försörjningskedjan?

Om sönderdelning och lagring

16. Vilka metoder använder ni för sönderdelning av GROT respektive andra skogsbränslen?
17. Vilka faktorer styr vilken metod ni använder för sönderdelning av GROT respektive skogsbränsle?
18. Var sker sönderdelning av GROT respektive skogsbränsle?
19. Vilka faktorer styr var sönderdelning skall ske?
20. Hur länge lagrar ni GROT respektive andra trädbränslen på hygge respektive vid vägkant?
21. Vilka faktorer avgör hur länge det lagras på respektive plats?
22. Hur länge lagrar ni grot respektive skogsbränsle på terminaler sönderdelat respektive ej sönderdelat?
23. Tar ni hänsyn till substansförluster som sker vid lagring?

Om terminaler

24. Vilka faktorer avgör om GROT respektive skogsbränsle ska transportera via terminal eller inte?
25. Vilken är terminalens funktion?
26. Hur många terminaler har ni?
27. Vilka faktorer styr hur många terminaler ni ska ha?
28. Använder ni er av entreprenörer som sköter terminaler?
29. Vilka faktorer avgör om ni ska ha egen terminal eller transportera via entreprenörs terminal?
30. Vilka typer av produkter passerar genom flödet?
31. Vilken är huvudprodukten för er på terminalerna?
32. Vad har varit avgörande för val av terminallokalisering?
33. Vilka är kriterier för terminallokalisering?
34. Har ni använt någon form av beräkningsmodell (optimering eller simulering) för att lokalisera terminaler?
35. Hur stor är kapaciteten på terminaler med avseende på lagring men även sönderdelning?
36. Vilka faktorer avgör hur stor kapacitet terminalerna bör ha?

Om kunders krav på leverensservice

37. Hur ser era kunders krav på leverensservice (leverensprecision, leverensflexibilitet och leverensservice) ut?
38. Hur påverkar era kunders krav på leverensservice försörjningskedjan?
39. Hur ser kundkraven ut med avseende på kvalitet?
40. Hur påverkar era kunders kvalitetskrav försörjningskedjan?
41. Finns det en tydlig kommunikation angående kvalitetskrav, exempelvis, återkommer kunder högre/lägre krav på kvalitet?

Övrigt

42. Har ni några planer på att byta skogsbränsle med andra leverantörer om det är mer lönsamt ur transportsynpunkt?
43. Vad skulle kunna förbättras för att få effektivare logistikupplägg?
44. Vad anser ni vara viktigt för en väl fungerande logistik gör GROT samt andra skogsbränslen

Frågeformulär transport och hanteringsföretag

Bakgrundsinformation om den som intervjuas och om företaget

1. Vem är du (befattning och bakgrund)?
2. Vad erbjuder ni för tjänster gällande GROT och annat skogsbränsle?

Om transportsystemet

3. Vad har ni för typ av transportfordon mellan vägkant och terminal respektive mellan terminal och konsument?
4. Hur långa är transportavstånden?
5. Vilka faktorer har avgjort vilka transportfordon ni ska ha?
6. När använder ni respektive fordon under året?
7. Om fordonen inte används jämt under året (är jämbördigt belagda), vad är anledningen till detta?
8. Vilka typer av resurser har ni för sönderdelning av GROT respektive skogsbränsle?
9. Vilka faktorer har avgjort vilka resurser ni har valt för sönderdelning?

Om beläggning av resurser

10. Hur är ni belagda för respektive tjänst (transport, sönderdelning, lagring) under året?
11. Kan ni använda era transportfordon till andra ändamål när ni inte använder dem till att transportera skogsbränsle?
12. Är beläggning ett problem för er?

Om leverensservice

13. Hur ser generellt kundernas krav på leverensservice ut (leverensprecision, leveranssäkerhet, leverensflexibilitet)?
14. Hur påverkar kundernas krav på leverensservice era aktiviteter?
15. Vilka krav har kunderna på kvalitet?
16. Vilka delar av kvalitetskontroll är ni ansvariga för?
17. Hr påverkar kundernas kvalitetskrav era aktiviteter?
18. Hur påverkas ni av konsumenternas möjlighet att flisa GROT och skogsbränsle?
19. Hur påverkas ni av konsumenternas möjligheter att lagra GROT och skogsbränsle själva?
20. Vilka faktorer avgör om GROT respektive skogsbränsle ska transportera via terminal eller inte?

Om terminaler

21. Vilken är terminalens funktion?
22. Hur många terminaler har ni?
23. Vilka typer av produkter passerar genom flödet (via terminal)?
24. Vilken är huvudprodukten för er på terminalerna?
25. Vad har varit avgörande för val av terminallokalisering?
26. Vilka är kriterier för terminallokalisering?

Övrigt

27. Är ni delaktiga i något samarbete kring att grotbyten mellan olika leverantörer för att få ökad transporteffektivitet?

28. Vad är viktigt för er för att uppnå en väl fungerande GROT och skogsbränslelogistik?
29. Vad anser ni att det finns för förbättringsområden för GROT och skogsbränslelogistik?