Strategic raw material supply for
the particleboard-producing industry in Europe

Problems and Challenges
STRATEGIC RAW MATERIAL SUPPLY
FOR THE PARTICLEBOARD-PRODUCING
INDUSTRY IN EUROPE
Problems and Challenges

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Errata

Page 1
Line 15: Mistake in the text: “The aspects presented in the thesis can also be applied to other wood-based panels such as OSB (ordered strand board) and MDF (medium fibre board) as these panels have the same raw material requirements as particleboard (Lundqvist and Gardiner 2011).”

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Page 16
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formaldehyde), 3% pMDI (polymeric diphenylmethane diisocyanate), and 3% others (Berglund and Rowell 2005; Niemz and Wagenführ 2012).
Abstract


Particleboard was invented to increase the utilization of wood and it soon became an important core material for furniture production. Nowadays, other industries such as the pulp and papermaking industry and the thermal energy recovery industry claim the same type of raw material. This leads to increasing competition and higher prices than in the past when that kind of wood raw material was widely available and of low price. The particleboard-producing industry is therefore seeking opportunities to reduce the competition and ensure the future supply of lignocellulosic raw material for their products.

The purpose of the work summarised in this thesis was to investigate the strategic supply of lignocellulosic raw materials for particleboard production and to evaluate alternatives for the supply of lignocellulosic raw material for particleboard production.

To encompass the complex field of strategic raw material supply, several publications have considered different stages along the supply chain. These papers range from empirical studies to practical tests on a laboratory scale. In this thesis, some of the papers are linked together, building the base for the overall results.

The results show that the task of increasing the supply of lignocellulosic raw material as primary raw material source is limited by several factors, but that improved product design coupled with a suitable recycling concept can greatly increase the availability of lignocellulosic raw material as a secondary source. Alternatively, the use of non-wood plants might be an opportunity to substitute wood as raw material but there are still some problems relating to the particle properties which must be overcome first.

Keywords: Biomass production; Lignocellulosic raw material; Non-wood plants; Particleboard; Pulp and paper; Recycling; Thermal energy recovery; Wood plants
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I would also like to thank Professor Dick Sandberg who started as principal supervisor and continued with his support even after the second year of the PhD study when he was no longer able to continue as supervisor at LNU.

Thanks also to the great team of Hus M, the personnel administration support and the departments of Building Technology, Built Environment and Energy Technology, Design, Forestry and Wood Technology, and Mechanical Engineering, who have given great support, discussions and interdisciplinary cooperation.
Appended papers

This thesis is a summary of the following papers referred to by their Roman numbers:


Contribution to the appended papers

For all the papers, the author of this thesis was the first author and the corresponding author. The author fulfilled the requirements regarding making substantial contributions to the conception and design, the acquisition, analysis and interpretation of data, participating in writing the paper, and giving final approval of the submitted version at all stages of the review process. Further, as corresponding author, primary responsibility was taken for communication with the journals during the manuscript submission, the review and publication process, and ensuring that all the journals’ administrative requirements were properly followed.
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Introduction

Background

The reason for the work summarised in this thesis was the need to find opportunities which help to avoid a shortage in the lignocellulosic raw material used in particleboard production. Such a shortage would lead to less raw material being available, higher competition and subsequently higher prices for the raw material. Therefore, the strategic raw material supply must aim to ensure a long-term supply of raw materials suitable for particleboard production.

It is difficult to consider the lignocellulosic raw material supply for the particleboard production on its own, since there are many and significant links between the traditional (pulp and paper, sawn wood) and new (bioenergy, biochemicals, engineered wood products) product markets (Hetemäki et al. 2014). The aspects presented in the thesis can also be applied to other wood-based panels such as OSB (ordered strand board) and MDF (medium fibre board) as these panels have the same raw material requirements as particleboard (Lundqvist and Gardiner 2011). The work has been focused on particleboard as it is still the most important wood-based panel in Europe for furniture making, with a production of 35.9 million m³ in 2014, of which more than two thirds (68%) were used in furniture manufacture. The production of fibreboards was 22.4 million m³ (MDF 72%), of which only slightly more than one third (38%) went into furniture production and almost the same amount into laminated flooring (37%). OSB, which is the third important wood-based panel in Europe, with a production of 5.8 million m³ in 2014, is far behind, and so is plywood with 4.6 million m³ (Eastin et al. 2015). Using the conversion factors for the different wood-based panels given by Mantau
(2012), the annual wood consumption including bark of the wood-based panel sector is approx. 110 million m³ wooden raw material.

The overall annual paper and paperboard production in Europe (98.6 thousand tonnes in 2014) has been slightly declining in recent years, especially for graphic papers, while the production of paperboard is increasing. The production of mechanical and chemical pulp also declined to slightly more than 38 thousand tonnes in 2014 (Valois et al. 2015). Trend projections for pulp and paper production in Europe assume a probable further decline in production (Hetemäki and Hurmekoski 2014). According to the Confederation of European Paper Industries (CEPI), the largest part of the raw material used in paper production is recycled paper, approx. 46%, followed by pulp, approx. 39%, and other, non-fibrous materials, approx. 15%. The wood consumption of this industry sector in 2014 was 146.7 million m³ wood raw material of which 72% was softwood (CEPI 2015).

Within the bioenergy sector, the thermal energy recovery using wood raw material to produce energy increased by 45% in the ten years to 2013, with a share of solid biofuels such as wood of 46%. The total primary energy production from solid biofuels in the 28 member states of the EU in 2013 was 3687 petajoules which is approx. 354.5 million tonnes of wood chips or 496.3 million m³ of solid wood equivalents, taking the raw material properties of Norway spruce as reference (Falster et al. 2005; Aguilar et al. 2015). Most of the raw material for thermal energy recovery is industrial wood residues, 58%, followed by direct sourcing, 36%, including trees in- and outside forests (Aguilar et al. 2015; Palacín 2015). According to different studies, the demand for wood may radically increase which would make it difficult to meet the demand for thermal energy recovery in the future, but these studies are also affected with considerable uncertainty (Mantau 2010; United Nations 2011; Hänninen and Mutanen 2014; United Nations 2015a).

It is difficult to compare the demands of the three competitors because of uncertainties regarding the solid wood equivalent, bark content and conversion factors. However, in spite of these uncertainties, the figures provide some estimation of the overall demand of the different industries. Considering the particleboard-producing industry in Europe only, the composition of the lignocellulosic raw material mix is approximately industrial residues, 56%, timber, 24%, and recycled wood, 21% (Sander et al. 2004). In the wood-processing industry, the amount of industrial wood residues can be up to 50% of the wood raw material. In the saw mill, the amount is in the range of 30-35% (Thrän et al. 2009). Regarding the total amount of recovered wood in the
European Union only estimates in the range of 45-81 million tonnes per year are available. More than half of this material goes into landfill, export, or incineration, and the rest is used mainly for combustion with only a small amount going into wood-based panel production (Sander et al. 2004). This means that half the recovered wood is waste, and that of the other half the main part is used for thermal energy recovery and only a small amount is suitable for wood-based panel production. The amount of recycled wood in particleboards is changing with country and with time. In 2010/2011 the approximate amount of recycled wood in particleboards produced in Germany was 33%, in Great Britain 55% and in Italy 89% (Meinlschmidt 2015).

Whether or not recovered wood can be re-used as raw material for the production of wood-based panels depends on its contamination by additives, especially hazardous chemicals (Bundesministerium der Justiz und für Verbraucherschutz 2002; Sander et al. 2004; European Panel Federation 2015). According to a study carried out by the Bayerisches Landesamt für Umwelt not all of the particleboard produced in Europe itself fulfils the requirements for re-use as raw material for wood-based panel production. In their study, 6 out of 9 panels exceeded at least one of the limits regarding hazardous agents (Bayerisches Landesamt für Umwelt 2015).

In general, the reasons for a shortage of raw materials vary. Basically it can be expected that both the world population and the world economy will continue to grow (United Nations 2004; United Nations 2015b) and this will also require higher levels of resources. Considering the European situation relating to the demand of wood which represents one lignocellulosic raw material, an increasing demand can be expected but, as the forest area is limited (United Nations 2011), the areas used for raw material supply must be used more intensively. In a simulation, Schwarzbauer and Stern (2010) showed that such an additional utilisation can be achieved by increasing prices for wood raw materials. An increase in price and demand for one type of wooden raw material also has an effect on other industries using lignocellulosic raw material (Trømborg and Solberg 2010; Abt et al. 2012). In addition, the recovery of energy from renewable sources is being promoted in Europe and this also leads to increasing demands for wood raw material (United Nations 2011). According to different findings, there are enough resources available to meet the demand for raw material for energy purposes, but Berndes et al. (2003) showed that the greatest uncertainties in such studies of energy crop production are the availability of land and the level of biomass production.
Nowadays, it is still possible on a global scale to access forest areas which have not yet been extensively used and therefore have a high stock of lignocellulosic raw material, but at the same time production areas in other parts of the world have been lost. Nevertheless, the access to backwoods to provide an additional source of wood raw material is connected with increasing costs for tapping. It is only a question of time until the point is reached where it either becomes too expensive to access new areas of high lignocellulosic raw material stocks or no additional areas are left. The effect would be to further increase prices for the lignocellulosic raw material, leading to more intensive utilisation of the areas already accessed and greater competition for the available lignocellulosic raw material.

This thesis seeks ways of avoiding or reducing the shortage of lignocellulosic raw material supply for particleboard production, as additional costs related to the raw material supply increase the costs of the product which, in general, are passed on to the consumer. Further, the increasing competition for the raw material may lead to the use of raw materials with poorer properties within the developed products in order to keep the costs low, and this may negatively affect the consumer. Increasing utilisation from the accessed areas may also have a negative impact on the consumer via the loss of socio-economic values such as recreation, nature, diversity, hunting etc. In the context of the available raw material and its specific properties, it is also necessary to consider other industries which use raw materials with similar properties. For this reason, not only particleboard production but also thermal energy recovery and pulp and papermaking are considered here, to evaluate, for example, whether the promotion of thermal energy recovery is directly or indirectly affecting other industries. The long-term view of the strategic raw material supply makes it necessary to consider not only the primary raw material source provided by nature but also the secondary raw material source which can be created by recycling. Regardless of the problems relating to just-in-time delivery or cascade-principle use, the design of the product has a strong impact on the amount of secondary raw material recovered and its properties during the recycling concept. In summary, the work described in this thesis was undertaken to find alternative ways to provide lignocellulosic raw materials with appropriate properties at low prices and with a long-term perspective, by using the construct of the strategic raw material supply.
Scope of the thesis

Strategic raw material supply

“Strategic” in the context of this thesis can be defined as “relating to the identification of long-term or overall aims and interests and the means of achieving them”, “designed or planned to serve a particular purpose” (Oxford Dictionaries 2015), “of or relating to a general plan that is created to achieve a goal […], usually over a long period of time”, or “useful or important in achieving a plan or strategy” (Merriam-Webster 2015). All these definitions combine the characteristics of a long-term perspective, a planned process, a (future) aim or goal and a defined method or theory to achieve that aim or goal. If these characteristics are implemented in the context of purchasing the raw materials necessary for the production of different products, the term “strategic supply chain” or “strategic supply chain management” comes up. The supply chain strategy includes the key dimensions: sourcing strategy, demand flow strategy, consumer service strategy, and supply chain integration strategy (Evans and Danks 1998). The supply chain is the network of actors, either within the boundaries of a single company or on a cross-boundary level connecting different companies, that transforms the raw material into distributed products (Hult et al. 2004). Basically, the strategic supply chain begins with the consumer who has a specific demand which initiates a response by the company leading to a sourcing strategy to provide the products and services to the market-place. Along the supply chain there is a high level of integrating and sharing company information, finances, operations and decision-making (Evans and Danks 1998). The interconnection between key processes allows companies to create a process framework that enables them to engage in co-evolvement rather than competition and facilitates product movement and coordination of supply and demand between supplier and buyer (Bechtel and Jayaram 1997), Fig. 1.
For an explanation of the strategic supply of raw material the concept of the strategic supply chain is not sufficiently comprehensive. The reasons are (1) the focus of the strategy is on cooperation within the supply chain and not on the supply as such, (2) the service or product flow ends at the consumer, which leads (3) to a linearity and unidirectional flow of raw materials. With an upcoming consumer pressure relating to environmental issues, companies are forced to develop environmental management strategies which must be implemented through the purchasing function (Lamming and Hampson 1996). A supply chain in which environmental management strategies are fully integrated includes product and packaging recycling, re-use, and/or remanufacturing operations, which means that the unidirectional flow of raw materials is extended to a semi-closed loop (Beamon 1999), Fig. 2. Whereas recycling is the collection and disassembling of products, resulting in a mixture of new raw materials, re-use is the collection and resale of products without additional processing, and remanufacturing the collection and resale after revision of the operability of a product (Beamon 1999).

Figure 1. Traditional supply chain showing the information flow related to a specific demand from the consumer to the supplier and the material flow of the raw material and products/services from the supplier to the consumer, modified after Beamon (1999)
The secondary material flow, which can be seen as a flow in a direction opposite to the traditional supply chain, can be described as “reverse logistics”. Reverse logistics concentrates on the flows of raw materials which have some value, can be recovered and can re-enter a supply chain as raw material. Reverse logistics thus differ from waste management as well as from green logistics where the collection and processing of waste and their environmental aspects are considered (de Brito and Dekker 2004). For this reason, the waste flow in Fig. 2 is illustrated differently from the rest of the secondary material flow.

The semi-closed loop of the material flow within the extended supply chain leads to a raw material supply concept which is close to the concept of strategic raw material supply. As mentioned above, a goal, a method to reach the goal, and a long-term perspective are the basis of a strategic process. As raw materials are limited, and as the raw material often changes its characteristics by processing when transformed into a product along the supply chain, it often becomes difficult to use all possible secondary raw materials after recycling within the same supply chain. Other companies within different supply chains can, however, show a higher potential and efficiency relating to the use of secondary raw materials. A strategic raw material supply is the efficient utilisation of the primary and secondary raw materials within a network of supply chains, leading to a long-term
perspective relating to the supply, a higher grade of recycling, and a longer time of raw material circulation before the raw material is degraded to disposal or waste.

There are pools of different raw materials in nature which provide sources of various primary raw materials in different amounts for different suppliers. After entering into an extended supply chain, the raw material is transformed into a product and ends its life in a recycling process where it is transformed into new secondary raw materials, entering a different extended supply chain and thus to a network of supply chains. An essential point in this concept is the recyclability of the different products at the end of their life time, leading to different amounts and properties of secondary raw materials. A more efficient use of primary raw materials, a higher grade of recycling and a longer time of raw material circulation, based on an efficient utilisation and transformation of the primary and secondary raw material within a network of supply chains, lead to a long-term perspective relating to the supply of raw materials which can be called “strategic raw material supply”, especially when it is possible to link the different conglomerates of strategic supply chains into a network.

In summary, the difference between raw material supply, strategic supply chain and strategic raw material supply can be interpreted in that the raw material supply is characterised by defining the amounts or stocks of different raw materials including their accessibility. By extending this concept to the use of the different raw materials including their retention time, flows and transformations/modifications within the system to ensure a long-term view, the characteristics of the strategic raw material supply are given. However, the focus is not on the flows of raw materials, which would follow the concept of the strategic (raw material) supply chain but on the raw material itself and on the amounts of different raw materials along the strategic supply chains. At this point, the dilemma of the wood-using industry becomes obvious due to its complexity, as wood as a “bio-composite” has multiple properties which have many different uses and modifications during application, and this makes general statements quite complicated.
Lignocellulosic raw material

Lignocellulosic raw material is a resource continuously provided by nature and encompasses a variety of specifications. Within the scientific classification, the plants producing lignocellulosic raw material relevant to this thesis are classified under the sub-kingdom Embryophyta, Spermatophyta (unranked) in the recent divisions Cycadophyta, Ginkgophyta, Pinophyta including Gnetophyta, and Magnoliophyta. The first three divisions are also defined as gymnosperms, and the fourth as angiosperms, also known as “flowering plants”. The angiosperms can be divided into dicotyledons (= plants which have two seed-leaves or cotyledons) and monocotyledons (= plants which have only one seed-leaf). In monocotyledons (non-wood plants), the vascular cambium, phloem and xylem, are not separated by the meristem so that the stem width does not grow (secondary growth) as it does in dicotyledons (wood plants) have it (Strasburger et al. 1991). The softwoods commonly used in the European wood-using industry such as pines, spruces, larches, and firs, are classified under the division Pinophyta, class Pinopsida, order Pinales in the family Pinaceae. The common yew (Taxus spp.) and redwood (Sequoia sempervirens) are classified under the same order but as different families (Strasburger et al. 1991; Bartels 1993). The hardwoods such as beech, oak, and maple, are classified under the division Magnoliophyta, Eudicotidae (unranked) and are also called eudicotyledons in different orders and families (Strasburger et al. 1991; Bartels 1993). Non-wood plants which are of interest such as different types of straw or reed canary grass (Phalaris arundinacea L.), are classified in different subfamilies under Monocotyledons (unranked), Commelinids (unranked), or Poales, family Poaceae (Strasburger et al. 1991), Fig. 3.
Figure 3: Section of the system of plants starting from the Spermatophytes (seed plants) down to examples of families of high commercial relevance relating to the production of lignocellulosic raw material. Bold: Branches showing examples for families of commercially relevant lignocellulosic raw material.
The diagram illustrated in Fig.3 shows a variation in the genotype of the species which leads to a large variation in phenotype of the different species and in chemical composition of the raw material (see e.g. Strasburger et al. 1991; Bartels 1993; Wagenführ 2007; Hartmann et al. 2009; Rowell et al. 2012). Table 1 presents a partition of various species producing lignocellulosic raw material which is or can be interesting for the particleboard producing industry.

**Table 1. Chemical composition as a percentage of the dry mass of selected species providing lignocellulosic raw material suitable for particleboard production or for a competing industry (Trischler et al. 2013)**

<table>
<thead>
<tr>
<th>Species</th>
<th>C</th>
<th>L</th>
<th>HC</th>
<th>A</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat straw ((Triticum aestivum \text{L.}))</td>
<td>38-41</td>
<td>8-15</td>
<td>29-31</td>
<td>6-6.3</td>
<td>(Bridgeman et al. 2008; Hartmann et al. 2009)</td>
</tr>
<tr>
<td>Miscanthus ((Miscanthus x giganteus))</td>
<td>43-49</td>
<td>11-19</td>
<td>29-30</td>
<td>2.6-6</td>
<td>(Hartmann et al. 2009; Hodgson et al. 2011)</td>
</tr>
<tr>
<td>Reed Canary grass ((Phalaris arundinacea L.))</td>
<td>30-43</td>
<td>8-11</td>
<td>25-30</td>
<td>1.3-6</td>
<td>(Dien et al. 2006; Bridgeman et al. 2008; Jansone et al. 2012)</td>
</tr>
<tr>
<td>Cup plant ((Silphium perfoliatum L.))</td>
<td>36</td>
<td>12</td>
<td>18</td>
<td>9</td>
<td>(Wulfes 2012)</td>
</tr>
<tr>
<td>Softwoods</td>
<td>40-45</td>
<td>25-35</td>
<td>25-30</td>
<td>0.2-0.4</td>
<td>(Fengel and Grosser 1975)(\text{Pettersen 1984})</td>
</tr>
<tr>
<td>Hardwoods</td>
<td>40-50</td>
<td>20-25</td>
<td>25-35</td>
<td>0.2-0.8</td>
<td>(Fengel and Grosser 1975; Pettersen 1984)</td>
</tr>
</tbody>
</table>

C: cellulose; L: lignin; HC: hemicelluloses; A: ash;

Differences can also be found between species regarding chemical components such as lignin (a polymer of aromatic subunits derived from phenylalanine) and hemicelluloses (the hexoses glucose, mannose and galactose, and the pentoses arabinose and xylose) (Whetten and Sederoff...
The three main monomers (monolignols) in lignin are the para-hydroxyphenyl (H-unit), guaiacyl (G-unit) and syringyl (S-unit). In gymnosperms (conifers or softwoods), lignin composed of G-units is generally predominant, whereas in dicotyledons (hardwoods) it is built up of a mixture of G- and S-units and in monocotyledons (non-wood plants) it is built up mainly of H-units (Hatfield and Vermerris 2001; Stephens and Halpin 2007). Differences in physical properties can also be found between the species, expressed for example in different fibre properties and types of cells, also between softwoods and hardwoods (see e.g. Horn 1978; Horn and Setterholm 1990; Toonen et al. 2007; Eder and Burgert 2010; Sjöström 2013; Trischler et al. 2014b). Although only librifrom fibres and fibre tracheids of the supporting tissue of hardwoods are “fibres”, the term fibre is frequently used for all kinds of wood cell due to their elongate form in both hard- and softwoods (Biermann 1996; Sjöström 2013). In this thesis, the term “fibre” is therefore also used as a synonym for a plant cell of longitudinal character.

The differences in fibre properties are due not only to differences in fibre dimensions but also to their differences in their chemical components. While the cell walls of dicotyledons (wood plants) consist of a cellulose-xyloglucan framework, embedded in a network of abundant pectic polysaccharides (homogalacturonan and rhamnogalacturonan I and II), with approximately the same amounts of both, the cell walls of monocotyledons (non-wood plants) contain less xyloglucans and pectin, cross-linked by glucoronobinoxylan and mixed glucans (Toonen et al. 2007). There are large differences between fibres from wood plants, fibres from non-wood plants and seed fibres with regard to cell-wall structure, such as number of secondary cell walls and microfibre angles (Eder and Burgert 2010). In contrast to wood fibres, bast fibres of non-wood plants such as flax and seed fibres such as cotton have a waxy cuticle which has the biological function of preventing drying and microbial entry. This waxy cuticle has to be removed during processing and thus affects the processing and quality of the fibres (Akin 2010). When particles are used comparable challenges occur. Whereas wooden particles show relative equal surfaces when processed after debarking of the stem, particles of non-wood plants show two different surface characteristics; an internal surface which is comparable to that of the wooden particles and an external surface which consists of a cuticle covered by a waxy layer and embedded silica (Barthlott and Neinhuis 1997; Wiśniewska et al. 2003; Shen et al. 2011; Trischler and Sandberg 2014). The waxy layer
contains of fatty acids, fatty alcohols and wax esters (Barthlott et al. 1998; Akin 2010). In addition, the particles of non-wood plants originate from different parts of the plant, the stalk (node and internode), leaf or leaf sheath which have different constructions and therefore different mechanical properties (Strasburger et al. 1991; Pahkala and Pihala 2000). Figure 4 illustrates different types of particle-sized and fibrous lignocellulosic raw materials interesting for particleboard production, from which plant and within which part of the plant they are derived and whether or not the surface is affected by a waxy layer.
Figure 4. Different sources of lignocellulosic raw materials which are considered in this thesis since they are or may be important for particleboard production, pulp- and papermaking or thermal energy recovery.
In summary, this chapter gives a rough overview of different primary sources of lignocellulosic raw materials (primary raw material, lignocellulosic raw material provided by nature or virgin raw material), which can be considered as a raw material source for particleboard production. In theory, many other species of interest for particleboard production can be included. However, the aim is to explain that there are differences regarding the raw material properties between wood (inter-species and intra-species-specific) and wood and non-wood plants because the species have a genetically different origin.

**Limitations and boundaries**

Any study of such a complex topic as the strategic raw material supply of lignocellulose raw material requires the setting up of boundaries. In general, the topic can be considered from three different points of view: economic, environmental and technical, and all the different kinds of industries using lignocellulosic raw material provided by nature (primary raw material) or reusing this raw material recovered by recycling (secondary raw material) can be considered. If the wood-using industry alone is considered, the complexity is still enormous. With regard to the sources of lignocellulosic raw material, there is a great variation in quantities and properties.

To define the boundaries of this thesis is important, as the design of the system strongly influences the research methodology and further the results. In this work, the focus has been on the strategic supply of lignocellulosic raw material suitable for particleboard production. In theory, as already mentioned in the introduction, other wood-based panels can also be included, but since particleboard is the main raw material for furniture production, the focus has been on particleboard production suitable for furniture.

To follow the concept of the strategic raw material supply, it is essential to consider the use and flow of the raw materials in a context which includes the main competitors and the supply chains to ensure the most efficient utilization. The pulp and papermaking and thermal energy recovery industries were selected as the main competitors of particleboard production. Each industry prefers raw material with specific properties leading to reciprocal effects on to the supply. In particleboard production, a change in the type of lignocellulosic raw materials used can make it necessary to adapt the process and product design. Fig. 5 illustrates where, within the wide scope of strategic raw material supply, the focus of the research was directed.
Figure 5. Characteristics of the study object, including the boundaries of this thesis and the appended papers. This figure illustrates the focus of the papers on three features: primary raw material supply (non-wood and wood plants), the interaction between the three industries considered, and process and product design.

In particleboard production, the lignocellulosic raw material (wood) is milled into particles of a length up to 15 mm and a diameter up to 4 mm. After screening and drying, the particles are glued together to a board under the application of heat and pressure. The conventional adhesives used are 90% aminoplasts such as UMF (urea melamine formaldehyde), 4% phenoplasts such as PF (phenol formaldehyde), 3% pMDI (phenolic methylene diphenyl diisocyanate), and 3% others (Berglund and Rowell 2005; Niemz and Wagenführ 2012). However, there are technical restrictions related to the properties of the lignocellulosic raw materials due to the relationship between the properties of the raw material and those of the board with regard to density, stiffness, strength, dimensional stability, internal bond strength, surface strength and appearance (Lundqvist and Gardiner 2011). Further, there is, for example, a positive correlation between the density of the board and its bending strength (Hacke et al. 2001). Other properties, such as dimensional stability, internal bond strength, surface strength and colour can be influenced by the size of the particles or by agents added during the production process.
which is especially interesting when alternative raw materials such as non-wood plants are used (Han et al. 1998; Xu et al. 2009).

For pulp and papermaking, the lignocellulosic raw material (wood logs) is first debarked and then chipped. The chips are sorted according to their size and, especially for kraft-pulping, according to their thickness, to permit uniform pulping. The optimum chips are those passing a 48 mm hole screen and a 10 mm (for softwoods) or 8 mm (for hardwoods) slotted screen, but being retained on a 7 mm hole screen. Smaller chips are called pins (retained on 3 mm) and fines (“unders”). Oversized chips (“overs”) are retained on the 48 mm hole screen (Biermann 1996). The lignocellulosic raw materials are mechanically/physically or chemically disintegrated into fibres, also called pulp. Paper is produced from a blend of different pulps and chemical additives after the fibres have been processed in different steps such as cleaning and modifications and finally mixed with water to a slurry (Bajpai 2012). These steps are important as the fibre morphology is the most influential factor determining how a sheet bonds together (Horn and Setterholm 1990). The slurry is spread to a sheet which undergoes dewatering, pressing and drying (Bajpai 2012). The paper properties are strongly influenced by intra-fibre bonding which influences the stiffness of the fibre and the inter-fibre bonding which is important for the sheet strength (Horn and Setterholm 1990).

Thermal energy recovery is the thermo-chemical transformation of lignocellulosic raw materials into energy. After mechanical reduction, the material is fed into plants which use the energy contained in the raw material to produce heat and/or electricity directly or to yield a gas which is afterwards transformed into different forms of energy (Hartmann et al. 2009; Hofbauer et al. 2009; Nussbaumer et al. 2009).

In general, the raw material enters a specific supply chain and re-enters or leaves it via recycling or transformation after a certain retention time, resulting in a mix of primary and secondary raw materials in the different supply chains. Therefore, the strategic raw material supply has to consider not only the “available” raw materials but also the product design which has a strong impact on the retention time, recycling availability, transformation of the raw material properties and re-use opportunities of the raw material. To consider the whole complexity of the strategic supply chain within this thesis is impossible. Therefore, limitations are also necessary regarding the strategic supply chain. Fig. 6 shows in the extended supply chain, shown in Fig. 2, the areas within the supply chain which have been considered.
The following limitations have therefore been defined:

- The strategic raw material supply is considered from a technical perspective
- The focus of the lignocellulosic raw material supply is on the primary raw material (lignocellulosic raw material provided by nature, virgin raw material)
- The lignocellulosic raw material is primarily considered as a raw material for particleboard production
- The preferred use of the particleboards is in furniture production
- Only three industrial sectors are considered: particleboard production, pulp and papermaking, and thermal energy recovery
- Within the extended supply chain, the focus is on the primary raw material supply of diverse raw materials and the production of boards from alternative sources of lignocellulosic raw materials
Aim

The aim of the thesis was to evaluate the strategic supply of different types of lignocellulosic raw materials suitable for particleboard production in relation to the two main competitors, namely pulp and papermaking and thermal energy recovery, and to discuss the obstacles and opportunities of strategic raw material supply.
Objectives

The purpose of this thesis was to estimate the potential strategic supply of lignocellulosic raw materials suitable for particleboard production in relation to the pulp and papermaking and thermal energy recovery, with a focus on the primary raw material supply. The following research questions were considered:

- What continuous supply of lignocellulosic raw material provided by nature (primary raw material) in Europe is suitable for particleboard production today?
- Will there be changes in quality and quantity of the lignocellulosic raw material available for this purpose in the future?
- Is it possible to increase primary raw material production or to use alternative sources of raw lignocellulosic raw material to ensure low-cost and efficient use of natural resources over a long-term perspective?
- Are there alternative sources of lignocellulosic raw material with the potential to replace the conventional lignocellulosic raw materials used in particleboard production?
- Can innovative, smart solutions in product design help to increase the amount of raw material suitable for particleboard production and thus help to ensure the production of good quality but affordable furniture?
Methodology

The methodology of the thesis is generally of a qualitative character due to the characteristics of being interpretive, experiential, situational and personalistic (Mayring 2002; Stake 2010). Further, characteristics of qualitative research are that “[...] the researcher him- or herself is an instrument, observing action and contexts, often intentionally playing a subjective role in the study, using his or her own personal experience in making interpretations” (Stake 2010). The most common methods for this kind of research are observation, interrogation, and examination of artefacts including documents (Mayring 2002; Stake 2010). Nevertheless, this thesis shows in some areas an integration of qualitative and quantitative characteristics as defined in the triangulation model where a combination of qualitative and quantitative analysis leads to a multi-layer approach as base for the results (Mayring 2001).

The methodological frame of this thesis with regard to the strategic raw material supply for particleboard production is illustrated in Fig. 7: Starting at the point “biomass production”, different types of lignocellulosic raw materials provided by nature (primary raw materials) with different material properties are available. Parts of the lignocellulosic raw materials leave the cycle, others enter it via recycling (secondary raw materials). The amount of recycled wood is influenced by the process and product design and has a strong impact on the amount of secondary raw material suitable for particleboard production. Therefore, the whole cycle of raw material flow is introduced even though it was mainly the first part – biomass production to product design – that was considered in this thesis.
Figure 7. The section of the strategic raw material supply suitable for particleboard production on which this thesis is focused

To provide information about the strategic raw material supply, it is necessary to characterise the relations between different players and future events. The amounts of available lignocellulosic raw material are changing with time and undergo strong fluctuations on the market. Changes in industrial sectors and in climate conditions make it difficult to estimate the raw materials available in the future. Additionally, the primary raw material depends on the species and not all of the primary raw materials available are suitable for particleboard production.

The strategic character of this topic requires an estimate of available raw material different from the estimation and extrapolation of the existing stock in combination with historical data about increment and harvest which would correspond more to the term “raw material supply”. It is necessary to find an easy way to estimate the continuous production of lignocellulosic raw material (biomass production) on a specific site. Further, it is necessary to derive solutions which allow a simple estimation of how the raw material properties may develop in the future as a result of changes in, for example, forest management, since changes in silvicultural operations have a strong impact on the properties and quantities of the primary raw material of the wood species continuously available. Since forestry provides raw materials mainly for the wood-using industries, the properties of the lignocellulosic raw material might also change in the future as the demands of the different industries change, and this again would have an impact on the type of primary raw material
available. For the purpose of the thesis, it is necessary to concentrate this mass of information into a tool suitable for strategic management which facilitates the planning and estimation of future characteristics of the lignocellulosic raw material. Of course, considering the multifunctional characteristics which forests and wood have as lignocellulosic raw material, such a “classification” has to be seen very critically. The author is aware of this but, nevertheless, someone has to take the first step. As such a conceptual study has to be considered to be very critical, this sub-study is still under consideration in the author’s team.

Another point which is always raised is the claim of some wood-processing industries, i.e. the particleboard producing and the pulp and papermaking industries, that the thermal energy recovering industry is increasing the competition for lignocellulosic raw material since it prefers the same type of raw material. Therefore, the strategic view in this thesis is to include the need of related industries and to make the competition visible. This has been done by setting the particleboard industry into a context, which includes the pulp and papermaking and thermal energy recovery industries.

Not only the raw material properties but also the processing and the production parameters have an impact on the properties of the product. Different product designs require different raw materials which have to be processed in different ways and under different production parameters. With regard to the process parameters, the focus has been on finding opportunities to include particles from non-wood plants as a substitute for wooden particles in conventional particleboard production, as their raw material is nowadays of relatively low economic interest. Further, the use of wheat protein (vital gluten) as a bio-based adhesive system has been studied. Alternative production parameters in combination with a new product design can make it possible to use alternative sources of primary raw materials and to increase the amount of secondary raw material in the recycling process. To evaluate the connections between the quantity and quality of lignocellulosic raw materials provided by nature (primary raw materials), product design and recycling (secondary raw materials), practical tests in the laboratory and descriptive methods have been used.
The key messages of the appended papers and their interactions

This chapter briefly explains the different appended papers and how are they linked together. The structure follows the chronological order of the papers introduced at the beginning of this thesis, from Paper I which introduces an idea for a model to estimate the individual biomass production of different species in specific sites to Paper V which presents an opportunity of including the particles of monocotyledons (non-wood plants) into conventional particleboard production.
Paper I

A model was introduced which allows the above-ground biomass production of different species on different sites to be estimated based on the mean annual temperature (MAT) and the mean annual precipitation (MAP), Fig. 8.

With the support of this model it is possible to estimate how much biomass can be produced on a given site. Further, it differentiates between species and makes it possible to see which species have a high and which have a low biomass production at a given site. Such a model is fundamental with regard to the availability of lignocellulosic raw materials provided by nature (primary raw materials) and for finding new potential raw material sources. With the support of this model, it was possible to show that biomass production per hectare can be increased in some regions by introducing new species. This model shows however only the estimated maximal biomass production and says nothing about the high risk connected with introducing a new species; in

Figure 8. Maximal potential biomass production for a species (dotted line) plotted as a function of the mean annual temperature (MAT) in °C for a fixed mean annual precipitation (MAP) in mm; the red part of the graph simulates the biomass production limited by MAT, and the blue part the biomass production limited by MAP (Trischler et al. 2014a)
reality, species show a wide range of biomass production on a single site, especially at the borders of their optimal growing conditions. Introducing foreign species which have a potential for a higher biomass production but are cultivated at the border of their tolerance regarding growing conditions can, therefore, result in a poorer biomass production than the native species.

Further, the model is a first version and may still include uncertainties. For example, the distribution of the precipitation during the year can have an impact on the growth of species, and this is one of the reasons why the model is limited to Sweden. However, it is here shown that the model also has the potential to be used for other regions within Europe. Nevertheless, the primary raw material, provided as biomass from different species, shows large differences in its raw material properties. While some of the lignocellulosic raw materials may be perfect for particleboard production, others may not fit at all. Therefore, it was necessary to find a way to group the lignocellulosic raw materials based on their properties. Since only pulp- and papermaking and the thermal energy recovering industry were considered in addition to the particleboard-producing industry, the grouping was limited to these three industries.

**Paper II**

An opportunity was found, based on the average material properties of different species, to define the primary raw material that is the most suitable for each of the three industries considered in this thesis, the pulp- and papermaking, the particleboard-producing and the thermal energy recovery industries. The results showed that all three industries prefer the same type of lignocellulosic raw material (the raw material provided by the same species), Fig. 9, which can easily result in increasing competition and higher prices for this type of raw material in the fact of increasing demands.
This evaluation was done by using average values for the raw material properties, the data such as density, fibre dimensions or calorific value being taken from the literature. For particleboard production, the chosen parameters were: density, wettability, pH-value, and amount of advantageous fibres; for pulp and papermaking: slenderness-ratio, flexibility coefficient, Runkel-ratio, and amount of advantageous fibres; and for thermal energy recovery: calorific value, ash content, and ash melting point. However, the raw material properties of wood plants within a single species and also the combination of different species can be strongly influenced by silvicultural operations. Wood plants need much longer to provide primary raw material (wood) compared to non-wood plants (straw, grass) and therefore, future changes in forest conditions and development, and the composition of species are of great interest for the wood-using industry. To formulate optional scenarios, the
majority of the impact factors of forest operations influencing the properties of wood raw material were concentrated into a tool for strategic planning.

**Paper III**

The strategic cube was used to define and illustrate the impact of silvicultural operations on the material properties of different wood species in order to make it possible to formulate some trends showing how the primary raw material can change with regard to changes within a single type of raw material and with changes in the composition of species providing different types of raw material, Fig. 10.

![Figure 10. Forest products (assortments of wood) and the related types of forests in the context of market-related parameters. Depending on the chosen product strategy, different types of lignocellulosic raw materials, here characterised as assortments of wood, can be produced; dotted and dashed arrows show the possible shifts in the competitive strategy (Trischler and Sandberg 2016)](image)

The shift between the different assortments of wood is shown in, Fig. 10, which shows that changes in the demand can lead to a change in forest type to provide a different primary raw material. Formulating this kind of phenomenon becomes important when structural changes occur among the
players on the market or when new players enter the market. Like all resources, lignocellulosic raw material which includes wood is also limited in quantity due to the area of production and climatic conditions. For example, if the demand for wood for energy purposes strongly increases there will be a shift in the direction of coppice forests based on hardwoods, and this will lead to less available area for forests devoted to softwoods for timber production. Generally, using such a tool for forest production has to be considered to be very critical because forestry is always providing a package of different products even when the focus is on one main product, and that is why this paper is still under processing. However, the limitation and the enforcement to clearly define the (main) product make the limitation of wood as a resource obvious and show eventual shifts between the different grades of wood or types of raw materials.

A permanent increase in the demand for wooden raw material is asking for an increase in the production of primary raw material if no alternative way of providing the required raw material can be found. Due to limitations in production area and climatic conditions, forestry will try to increase the production of a single species on the available land and decrease the time of the rotation cycle to meet the increasing demand. Options are larger areas of forest plantations and more intense cultivation of foreign species, for example. These are only two scenarios, but they would both have an impact on the properties of the lignocellulosic raw material when considering the strategic cube, Fig. 10.

An increasing demand for one type of raw material leads to greater competition and higher prices for the raw material, as it is a limited source – which is demonstrated very well in Fig. 10. For the particleboard producing industry it might therefore be necessary to concentrate on alternative raw material sources such as lignocellulosic raw materials from monocotyledons (non-wood plants). If the particleboard-producing industry succeeds in using lignocellulosic raw material from non-wood plants as a direct substitute for wooden raw material it would have great advantages with regard to the purchase of their lignocellulosic raw material, especially, as their main competitors show low interest in these kinds of raw material. This is also one reason why there is considerable ongoing research into this topic.
Paper IV

Reed canary grass (RCG), which might be a potential source of lignocellulosic raw material suitable for particleboard production, was used to produce particleboards. MUF (melamine urea formaldehyde) and wheat protein (vital gluten) were used as adhesives to produce particleboard with RCG either alone or in combination with wood, Fig. 11.

It was possible to produce particleboards of RCG, Fig. 11, but none of the boards passed the requirements of the relevant standards. However, the tests were helpful for the evaluation of the production parameters and properties of particleboards containing large amounts of lignocellulosic raw materials of non-wood plants such as RCG. The particles were used in a natural manner to obtain a reference value without any pre-treatment and because any additional processing of the raw material leads to increased production costs which are to be avoided. The results showed that it is essential to find an efficient technique for surface treatment of the raw materials from non-wood plants if they are to be used in combination with wood in conventional particleboard production. Unfortunately, such pre-treatments are cost- and time-assuming and, as a result, all the cost-advantages of these non-wooden lignocellulosic raw materials such as agricultural residues are lost. Further, there is a logistical problem which the lignocellulosic raw materials have in common: Agricultural residues, in particular, are often available in large amounts only once or at the most twice a year and they have to be stored over the rest of the year without losing their mechanical properties. It was therefore necessary to find a way to overcome both the surface treatment and the logistical and storage problem.
Paper V

A technique for an efficient surface-treatment of particles of monocotyledons (non-wood plants) was presented which can be integrated into particleboard production and helps to solve some of the problems regarding the storage of the raw material, Fig. 12.

Figure 12. Particleboard production process with an integrated surface treatment of monocotyledons (non-wood plants) based on anaerobic digestion (AD). CPH – combined heat and power (Trischler and Sandberg 2015a)
As it is difficult to use reed canary grass (RCG) and other non-wood plants in their natural state in particleboard production, it is necessary to find a way of treating this raw material in a way which is both cost- and time-efficient, and the storage problem must also be solved. By using enzymatic surface treatment based on the process of anaerobic digestion, possibly in combination with ensilage, a concept was presented for how a surface treatment of non-wooden particles can be included in the particleboard-production process in a value-added manner. This process would solve the problem of degradation during storage, reduce the time for pre-treatment, as this surface-treatment can be started already during storage, and have as output not only the pre-treated particles but also a valuable by-product giving this process a value-added character.

Another alternative way of increasing the available lignocellulosic raw material is by increasing the amount of secondary raw material, Fig. 7. This alternative is not explicitly included in this thesis, but it has to be considered. The product design of particleboards, the production parameters and the processing of the raw material have a strong influence on the amount and properties of the secondary raw material which can be used for the same purpose. This would require a production process where a recycling concept such as a specific finish (surface treatment) of the panel is included in the design and alternative adhesives e.g. bio-based adhesives such as wheat gluten can be used (Trischler and Sandberg 2015b; Trischler and Sandberg 2015c). Unfortunately, due to limited time and resources within the PhD-study time, it was not possible to carry out more research in this direction.
Results

The overall result of the work described in this thesis is that it is difficult to obtain alternative or new types of primary raw material suitable for particleboard production without changing the process or product design. Problems are caused either by the climatic conditions on the site or by the raw material properties and alternative solutions such as new product design in combination with smart recycling concepts are therefore becoming more important. In this chapter, the statement about the overall result is explained in more detail.

The availability of primary raw material exemplified on four different sites in Europe

One of the most interesting questions relating to the strategic raw material supply of lignocellulosic raw material is the one facing the future supply. Is it possible to use other species with higher biomass production as an alternative source of primary raw material? What will happen with the supply as a result of climate change? To analyse or estimate the existing stock of primary raw material is not helpful in answering those questions, and a model to estimate the above-ground biomass production for different species on different specific sites defined by MAT (mean annual temperature) and MAP (mean annual precipitation) was therefore developed. Although it is just an idea and has not been verified, the model can be used to provide a first estimate of the maximum biomass production on different sites in Europe: The MAT and MAP were chosen for Luleå: 1.4 °C and 494 mm, Växjö: 6.5 °C and 649 mm, Graz: 8.3 °C and 838 mm, and Poznań: 8.5 °C and 507 mm. The changes in MAT and MAP can also be seen as climate-change scenarios for one site only, Fig. 13.
Figure 13. Above-ground biomass production of some selected species at four different sites in Europe. Wood species which show a biomass production lower than 1 Mg ha\(^{-1}\) a\(^{-1}\) are expected to be seasonal only, as they hardly survive the winter on that site.
When the values for MAT and MAP are compared with the distribution of the above-ground biomass production, it becomes evident that at the northern sites (Luleå) temperature is the restricting factor, in the more continental sites (Poznań) the precipitation, and sometimes both parameters depending on the species (Växjö and Graz). The model further shows that it is difficult to introduce new species on sites with extreme climate conditions in the hope of increasing biomass production. Firstly, the foreign species would grow at the border of their ecological tolerance which means that cultivation of this species is connected with high risks, and secondly, only a small amount of their potentially high productivity can be accessed. On sites with more advantageous climate conditions, the introduction of foreign species can lead to a strong increase in the annual biomass production when, for example, the biomass production of spruce (*Picea abies*) and pine (*Pinus sylvestris*) is compared with that of paulownia (*Paulownia* spp.) or miscanthus (*Miscanthus* spp.) in Fig. 13.

Although some of the species have a larger above-ground biomass production than others, the huge breakthrough seems missing. This would actually mean that the chance of finding an alternative source of primary raw material is quite low – based on the modelled estimated maximum annual above-ground biomass production and the species considered. However, some of the species show a high biomass production, especially on sites with more favourable climate conditions, but is it beneficial to concentrate on them? The commercial relevance based on the annual above-ground biomass production of the different species and the suitability of their lignocellulosic raw material for the three industries considered in this thesis, particleboard production, pulp- and papermaking and thermal energy recovery, can help to answer this question.
The commercial relevance of the primary raw materials for the different sites for particleboard production, pulp and papermaking and thermal energy recovery

In this chapter the results are projected in two different ways to illustrate their commercial relevance. In Fig. 14a - 17a, the species are plotted relative to each other in relation to the above-ground biomass production and their raw material properties relevant for the particleboard producing, the pulp- and papermaking and the thermal energy recovery industries. For commercial relevance, Fig. 14b - 17b, the size of the dots shows the integrated value of biomass production, the raw material properties and the rotation time.

The figures show that generally the softwood species and the young fast-growing hardwood species are of great interest for the three industries because of their relatively advantageous raw material properties and high biomass production. Taking into account the commercial relevance including the rotation time in addition to the raw material properties for the three industries and the biomass production, it is evident that with a warmer and dryer climate there is a shift from the softwood species (Fig. 14b) with their high biomass production under cool conditions towards the fast-growing hardwood species (Fig. 17b) with their relatively much higher biomass production and shorter rotation time.
Figure 14. Different species plotted based on (a) their raw material properties with regard to the pulp and papermaking, particleboard production and thermal energy recovery vs. biomass production, and (b) their commercial relevance including biomass production and raw material properties the rotation time for a site (Luleå) with a mean annual temperature of 1.4 °C and a mean annual precipitation of 494 mm.
Figure 15. Different species plotted based on (a) their raw material properties with regard to pulp and paper production and thermal energy recovery vs. biomass production and raw material production and commercial relevance, including biomass production and raw material properties (b) their rotation time for a site (Växjö) with a mean annual temperature of 6.5 °C and a mean annual precipitation of 649 mm.
Figure 16. Different species plotted based on (a) their raw material properties with regard to the pulp and papermaking, particleboard production and thermal energy recovery vs. biomass production, and (b) their commercial relevance including biomass production and raw material properties the rotation time for a site (Graz) with a mean annual temperature of 8.3 °C and a mean annual precipitation of 838 mm.
Figure 17. Different species plotted based on (a) their raw material properties with regard to the pulp and papermaking, particleboard, and new production and thermal energy recovery vs. biomass production and (b) their commercial relevance including biomass production and raw material properties with regard to the pulp and particleboard production.
The sustainable amount of primary raw material is restricted by climatic conditions and can therefore not be increased at will. The three industries prefer the same type of raw material, and it can be expected that an increasing demand for primary raw material will lead to more intensive forms of cultivation. This would lead in the extreme case to plantations of young fast-growing species and decreasing rotation times to meet the increasing demand for lignocellulosic raw material. A decrease in rotation time alone is already affecting wood-using industries negatively due to changes in the quality of the wood raw material, with a relatively larger amount of juvenile wood. In combination with climate change towards a dryer and warmer climate, such species would be mainly from the families of hardwoods. This trend would also affect other wood-using industries as it would have a strong impact on the composition of available raw materials. For this reason, the particleboard industry is continually testing alternative sources of raw material such as lignocellulosic raw material from short rotation coppice and non-wood plants (monocotyledons).

**Alternative sources of lignocellulosic raw material**

An alternative source of lignocellulosic raw material is non-wood plants such as miscanthus and reed canary grass, which have a high biomass production and a short one-year rotation time. They are also characterized by low competition between the three industries; even for thermal energy recovery they are for example less favourable than short rotation coppice. Nevertheless, following the concept of Steinmann and Schreyögg (2005), Fig. 18, it is necessary that the lignocellulosic raw material from non-wood species is used as a direct substitute for the wood raw material, otherwise the particleboard industry would shift from being a core market (cost leadership) towards being a niche market (differentiation) which makes it questionable whether the focus of competition can still also be on costs.
The raw material from non-wood species must be pre-treated before it can be used for particleboard production to make it more like the particles of wood plants conventionally used in particleboard production. Tests have shown that it is possible to substitute wood by 75% in weight of particles from non-wood species and still achieve good surface properties when the particles of the non-wood species are concentrated in the core-layer and the wooden particles in the outer-layers Fig. 19. In theory the substitution effect increases with increasing thickness of the board, as the extent of the core-layer becomes relatively greater.

Figure 18. The strategic cube (Steinmann and Schreyögg 2005) is a strategic management tool which helps to define the product strategy in connection to the market. The red arrow shows the expected shift of the product “particleboard” when concentrating on lignocellulosic raw material from non-wood species only instead of finding an opportunity to use their raw material as a direct substitute for wooden raw material which would require process and product development.
Nevertheless, using particles of non-wood species such as straw or grass in their natural way leads to boards with a low mechanical performance due to bonding problems when conventional adhesives such as MUF (melamine urea formaldehyde) are used. Therefore, a pre-treatment process which leads to better usability of the monocotyledon particles and which can easily be integrated into the conventional particleboard production process has to be developed.

Another way of increasing the amount of lignocellulosic raw material suitable for particleboard production is by increasing the amount of suitable secondary raw material within the supply chain. Unfortunately, the secondary raw material shows a wide range of properties, and the best way of ensuring a suitable secondary raw material for one’s product is therefore by recycling one’s own products. An alternative design of a particleboard in combination with changes in the production process parameters can increase the amount of secondary raw material which can be recycled and re-used in particleboard production. Alternatively, one of the competitors can profit from the new type of secondary raw material. The product design should include relatively mild thermal treatment during processing, a non-hazardous, bio-based adhesive system which would allow accumulation of the adhesive system during different recycling cycles, and a surface treatment of the board which can easily be separated from the lignocellulosic component of the board at the end of product life-time or be integrated into the recycling concept (Trischler and Sandberg 2015c; Trischler and Sandberg 2015b). The recycling of such boards should lead to nearly 100% re-use of the lignocellulosic raw material in particleboard production.

*Figure 19.* Particleboard produced from wooden particles (Norway spruce and Scots pine) and non-wood particles (reed canary grass) in the layer. (a) board thickness of 30mm with a substitution of 50%, (b) board thickness of 20mm with a substitution of 75%
Discussion

In this thesis, the strategic supply of lignocellulosic raw material suitable for particleboard production in relation to the two competitors, pulp- and papermaking and thermal energy recovery has been considered. In the introduction, the terms “strategic raw material supply” and “lignocellulosic raw material” were explained. Due to the wide scope of the research area the thesis covers only the section with a focus on primary raw material (lignocellulosic raw material provided by nature, virgin raw material) and the use of non-wood species (monocotyledons) as a substitute raw material. It has only been possible to use average data values found in the literature. Further, because of limited resources and time, it has not been possible to verify all the conclusions from the theoretical studies by practical tests, which increases of course the risk of errors due to a greater possibility of misinterpretation and misleading information.

The term “strategic raw material supply” is nowadays not frequently used in the literature and no review of the relevant literature was therefore possible; Google scholar® (November, 24th 2015) gave, for example, six results for “strategic raw material supply” with half of them being citations and Scopus® (same date) gave only one result. Instead, the term as such was explained by using literature from related disciplines. Although the topic is up-to-date, the term is quite uncommon in the literature. Further, when the frequencies of the terms “strategic supply” and “sustainable supply” are compared, the second term is much more frequent in the literature. This may be due to the popularity of the term “sustainable” related to this field, originally formulated by von Carlowitz (1713) in “Sylicultura oeconomica”, which became commonly known after being mentioned in the UN report “Our Common Future”, also known as the “Brundtland Report” (United Nations 1987).

However, focusing on the sustainable supply would complicate the research in the field of “strategic raw material supply” even more, as industry-
external factors such as governments, stakeholders, consumers and not only industry-internal factors such as rival supply chains have to be considered (Gold et al. 2010). The strategic view of the material supply wishes to include characteristics of sustainable supply chains such as those presented by Linton et al. (2007) that extend beyond the core of supply chain management to include product design, the handling of by-products, product life time, re-use and recycling at the end of product life time, while the focus of strategic supply is on how the design and structure of the supply can meet the competitive market pressures and demands that face a company (Cousins and Spekman 2003). The supply management, however, acts as an interface of the company between the consumers’ needs and the suppliers’ requirements and bridges the gap between downstream the and upstream supply chains (Lintukangas et al. 2014; Gurtu et al. 2015). As a basis for the formulation of the term “strategic raw material supply”, the extended supply chain was used.

The interpretation of the term “strategic raw material supply”, deduced from related and combined disciplines, is of course characterised by strong subjectivity. In the worst case, this leads to a phenomenon present for example in the area of supply chains addressing the impacts on the environment where many different terms such as “green supply chain”, “eco-friendly supply chain” or “sustainable supply chain” exist for essentially the same research area and cause confusion (Gurtu et al. 2015). In this thesis, that problem should not arise for two reasons: (a) the term “strategic raw material supply” or related terms such as “sustainable raw material supply”, “intelligent raw material supply”, and “sophisticated raw material supply “ are not yet frequent in the literature. If this term develops over time it will result in an improvement instead of parallel interpretations, (b) the terms: “strategic”, “raw material” and “supply” by themselves are also more narrowly defined than “sustainable” or “green”.

If only the raw material situation within a supply chain is considered and not the management aspect, we are at the material supply. When the different supply chains are compared, the concepts of the extended supply chains with a semi-closed loop (Beamon 1999) or closed loop (Guide et al. 2003; Fleischmann et al. 2005) characterises the situation best. The strategic raw material supply then automatically gains the long-term perspective which separates it from the simple raw material supply, estimating the available stocks but not their potential changes or influences.

Within the scope of the extended supply chain, it was necessary to decide on a starting point and an area on which the research should be focused. The
long-term perspective is to seek alternatives rather than to make estimates about the current stocks of the various lignocellulosic raw materials. Strategic supply means understanding the pressures and uncertainties related to the supply, such as e.g. competition, and how to react to these pressures (Cousins and Spekman 2003; Sahling and Kayser 2015). Therefore, the dynamics of the impact factors require alternative methods to estimate stocks (Cox 2015), such as models estimation and comparing the current biomass production of different species in different regions (Trischler et al. 2014a), in combination with models helping to characterize the properties of the raw materials and the competition on the market (Trischler et al. 2014b; Trischler and Sandberg 2016), as well as considering alternative sources and methods to ensure their supply, such as the use of non-wood plants which generally show a low competition or implement a product design which allows better re-use of the lignocellulosic raw material (Trischler et al. 2013; Trischler and Sandberg 2014; Trischler and Sandberg 2015b; Trischler and Sandberg 2015a). The focus of the research in the sub-studies included in the thesis was limited to the scope of primary raw material supply. This includes the supply of different types of primary raw material, their raw material properties, their suitability for particleboard production and their competition on the market.

With regard to competing industries, only the pulp and papermaking, particleboard producing, and thermal energy recovery industries were considered. This means that only an incomplete picture of the overall raw material accessibility can be drawn, but they were shown to be strong competitors for the same type of lignocellulosic raw material, which is supported by the related literature, see e.g. Schwarzbauer and Stern (2010), Trischler et al. (2014b) and Mantau (2015). The method used in the sub-study of this thesis is however based on average values or estimations and thus constitute a relative ranking. It is excellent for giving an overall structure or estimate, but the absolute values have to be considered critical. Further, if other species, such as more foreign tree species are included, the results of this study will most likely change. No proper method for the quantification of the availability of primary raw material was available. Therefore, a model was developed including the most common species for forest production in Europe (Trischler et al. 2014a). Since the estimation of biomass production in this model is based partly on critical parameters and since there are still a lot of open questions, the model should be used with care even when the results look appropriate. However, it is a great idea and when it has been tested, verified and optimized, this model can provide the base for an alternative and very
efficient way of estimating the biomass production of diverse species on different sites.

In general, it was shown that the source of primary raw material is very limited, see e.g. Fenning and Gershenzon (2002) and Berndes et al. (2003). Of course, forms of intensive cultivation such as forest plantations can increase the production per annum of specific types of raw material per area, see e.g. Fenning and Gershenzon (2002), Siry et al. (2005), Fenning and Gershenzon (2002) and Trischler and Sandberg (2016). The results presented in this thesis also show that the most advantageous raw material sources are already being fully used. It can be supposed that other foreign species suitable for cultivation in Europe of higher commercial relevance than those considered in this thesis would already have been cultivated in forest plantations. Therefore, the probability of finding an alternative source of primary raw material which combines both high yields of biomass production and advantageous raw material properties is relatively low.

The results obviously show that climate change has a strong impact on the quality and quantity of the lignocellulosic raw material due to changes in the ecological site conditions. As the different species each have specific ecological optima, their vitality and power of competitiveness relative to each other are changing with the climate, and forest management has to react to these changes (Prentice et al. 1993; Spittlehouse and Stewart 2004; Boisvenue and Running 2006; Allen et al. 2010; Sturrock et al. 2011). The expectation of a warmer and dryer climate and the current tightening competition of lignocellulosic raw material conventionally used for particleboard production make agricultural residuals and short rotation coppices interesting as an alternative source of lignocellulosic raw material.

In this thesis, it has been shown that focusing on non-wood plants (monocotyledons) as a primary raw material can be problematic, because of their differences compared to wooden particles with regard to particle surface, chemical consumption and mechanical properties (Barthlott et al. 1998; Grigoriou 2000; Boquillon et al. 2004; Trischler and Sandberg 2014). Further, residuals are not the primary product quality on which management is focused and it is assumed that they are available in a wide range of qualities leading to a large variation in properties. The differences in surface properties of the particles make pre-treatment necessary and this requires an additional processing step. Pre-treatment of the non-wood plant particles is essential to make them suitable as a substitute for wooden particles, as the particleboard would otherwise shift from a cost-orientated core market to a diversification-
orientated niche-market. Probably the most critical fact related to the use of non-wood plants in the form of residuals is that, after a market is established, the price of the raw material can be expected to increase, which would legalize the one great advantage this raw material has nowadays. As most of the residues from non-wood plants are available only seasonally, a logistical concept also has to be applied to ensure continuous accessibility and a high quality of the raw material. In theory, many of the drawbacks related to the logistical complexity and the use of non-wood plants as a substitute for wood plants in particleboard can be solved by using anaerobic storage and treatment techniques (Trischler and Sandberg 2015a). Unfortunately, extensive practical tests are still missing.

Short rotation coppices such as willow or poplar were not tested in this work. The examples in the literature show a decrease in the mechanical properties MOR (modulus of rupture) and MOE (modulus of elasticity) but an increasing internal bond strength with increasing amount of particles from willow (short rotation coppice). Boards produced from 30% and 50 or 100% willow particles with a density of 700 kg/m$^3$ or higher, pressing times of 8 or 18 seconds per millimetre and pressing temperatures of 185 °C or 180 °C fulfilled the requirements of the relevant standards (Sean and Labrecque 2006; Warmbier et al. 2013a; Warmbier et al. 2013b).

Another alternative source of lignocellulosic raw material is the secondary raw material (lignocellulosic raw material gained via recycling), which was not explicitly tested within this project but is considered in theory through the extended supply chain. Trischler and Sandberg (2015b) showed that recycling starts not with a reverse logistic concept but with the product design. Changes in the product design enable changes in the process parameters and these again have an impact on the quantity and the properties of the secondary raw material which becomes available during recycling and vice versa. There are many reasons for a company to invest in such a product design, not only with regard to lowering competition. Other industrial sectors within the wood-using industry e.g. the pulp and papermaking industry, can also profit from changes in product design by contributing to the establishment of new products and new product segments. In addition to increasing the amount of available raw material suitable for diverse purposes and the argument of “sustainability”, consumption can be increased through being able to offer healthier products and by lowering the inhibition threshold for buying a new product by ensuring recycling opportunities that make it easier to get rid of the products again. Further, once a reverse logistic and recycling concept is established to ensure
that the greater part of the raw material is being recycled, it can be of interest for the company to invest more in the quality of the raw material and product as they are kept for a longer time within the product life cycle. Additional research and development in that area is however necessary, including market-relevant studies and product prototypes.

Considering the overall topic of strategic raw material supply and discussing it in a wider context several lessons with regard to society can be drawn. In general, there is a cost pressure on the companies producing a “standard product” such as particleboard, as cheap products ensure proper selling rates in that product portfolio (Steinmann and Schreyögg 2005; Schroeter 2013). The production of particleboards has over the years been so optimized (Klauditz 1966; Irle and Barbu 2010) so that any change resulting in higher material input or effort tends to push the particleboard as a product into a nice market. However, innovation towards more sustainable products has been shown to be a promising alternative to escape the cost spiral (Nidumolu et al. 2009). On the one hand, innovation is asking for stuff and resources but, on the other hand, increasing selling rates and a market leader position are compensating for this. Additionally, if the cumulative variable costs in particleboard production are considered, Fig. 20, it becomes obvious that saving in the “administrative” part or investing in the economic and market relevant environment of the company (both have to be considered as transaction costs) of course is beneficial, although the total costs related to the raw material supply and the production process remain unchanged. For particleboard production, the costs related to raw materials are approximately 40%, and the raw material costs together with the production-process-related costs are more than 70% of the total costs (Spelter 1997). Small changes thus have a strong impact on the total costs.
Considering the absolute costs in Fig. 20, there is clearly a strong increase in the total costs over the years. However, if the relative costs are considered, there were no great changes between the different cost units over time. Those are costs on the US market, but it can be assumed that the picture is similar for the European market. To quantify the total costs, the price index for particleboard is helpful, Fig. 21.

The relative decline in the price of particleboard illustrated by the price index in Fig. 21 strengthens the theory that cost leadership is the driving force in particleboard production (Schroeter 2013). Due to the high percentage
which the raw material and production process have on the total costs of particleboard production, small changes have a relatively large impact on the total costs of the product. Therefore, shifting the production towards lower production costs, decreasing employment in production and considering a strong establishment and expansion of the thermal energy recovery industry (Hetemäki and Hurmekoski 2014; Aguilar et al. 2015; United Nations 2015a) as critical is a logical reaction. The development of the renewable energy sector is important, but it should not be forgotten that the wood products and the pulp and paper industries are several times more beneficial in the creation of value and employment than the direct thermal energy recovery of the lignocellulosic raw material (Janssens 2003).

A more efficient use of the lignocellulosic raw material in a cascade manner would optimize its use and integrate its final use for energy recovery (Haberl and Geissler 2000; Mantau 2010; Mantau 2015). The wood-based panel industry uses less lignocellulosic raw material than its two competitors considered in this thesis; nevertheless, changes in product designs or innovative product-service systems within this sector can help to lower the competition for the primary raw material (Handfield et al. 1997; Bovea and Vidal 2004; Besch 2005; Trischler and Sandberg 2015b). Proper product design and the combination of different raw materials can have a positive impact on the life cycle perspective as the resource-intensive treatment of other raw materials can then be avoided, but only when it is possible to recycle them (Björklund and Finnveden 2005). However, the beneficial effect of the interplay of the cascade-use of lignocellulosic raw materials, other raw materials and bioenergy, depends on the quantity and quality of the available biomass (Sathre and Gustavsson 2006; Sathre and Gustavsson 2009).
Conclusions

In this thesis, the concept of strategic raw material supply of lignocellulosic raw material suitable for particleboard production has been introduced and the raw material and its sources evaluated. The strategic aspect of the topic required for more than just estimating current available stocks. The availability of raw materials is changing continuously, especially in the case of resources provided by nature. A season with extreme weather conditions or a calamity can lead to short-term fluctuations in the availability and price, and climate change and changes on the market can lead to long-term changes.

It is difficult to increase the quantity of the primary raw material without a loss in quality. For particleboard production, the substitution of the commonly used wooden raw material by other lignocellulosic raw materials e.g. monocotyledon raw materials (lignocellulosic raw materials of non-wood plants) without any further changes within the product design or production process is nowadays also disadvantageous. With regard to the preferred raw material use by the two competitors considered in this thesis, the pulp- and papermaking and the thermal energy recovery industries, it can be concluded that for all three the same type of lignocellulosic raw material is beneficial. This strengthens the argumentation of the particleboard-producing and pulp-and papermaking industries that the promotion of thermal energy recovery from wooden biomass is tightening competition. A climate change towards dryer and warmer climate changes the mix of the available lignocellulosic raw material. By investing in innovation and technical applications, production processes and product design, several problems regarding the competition and shortage of raw material supply can be overcome. Further, it may be possible to ensure some amount of secondary raw material by developing associated
with the product design a recycling concept including reverse logistics. By doing so, not only can the strategic supply of raw material be easier to achieve – which would ensure easier purchasing – but the consumer may also be motivated to buy more, which positively influences sales.

In summary, investing in a new product design and production technique can lower the competition for the primary raw material and significantly increase the amount of non-hazardous lignocellulosic raw material during recycling. By increasing the amount of secondary raw material in the raw material flow cycle within the strategic supply chain of industries using comparable raw materials, the pressure of competition is taken from the primary raw material. Therefore, for cost-driven products such as particleboards it can also be supposed that creativity and innovation create the potential for money while purchasing and sales determine its flow.
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