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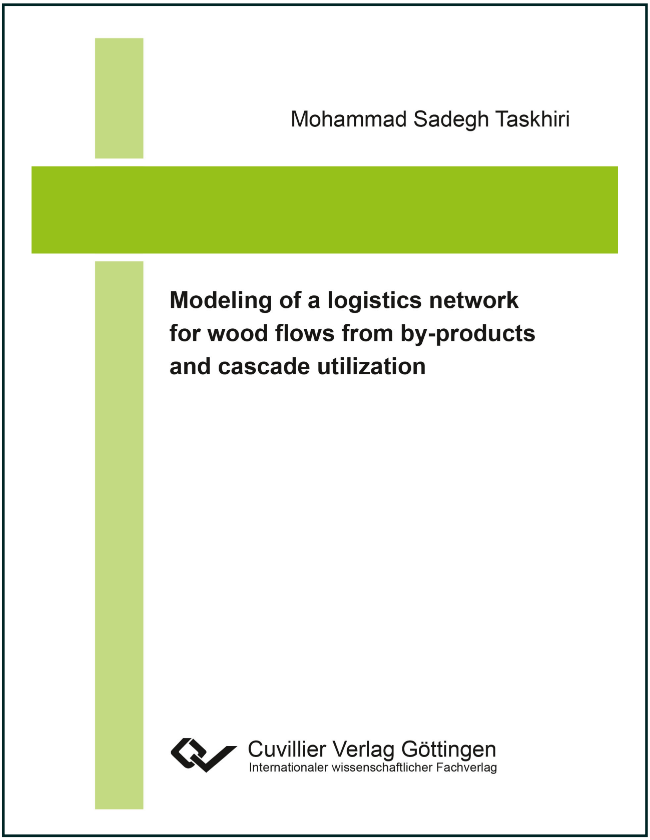
Modeling of a logistics network for wood flows from by-products and cascade utilization



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1 Introduction

At 4.03 billion hectares, nearly 30% of Earth's land surface is covered with forests (FAO, 2010). This forest land contributes more than two-thirds of the terrestrial gross primary production (GPP) (Beer et al., 2010), which is closely coupled with physical (i.e., abiotic) and ecological (i.e., biotic) changes as well as 80% of the earth's total plant biomass production (Kindermann et al., 2008). The forest sector is an important source of income in many countries and provides at least some income for an estimated 18% of the world's population (FAO, 2014).

This work focuses on Germany, one of the most forested countries in Europe. Its forests supply more than 50 million m³ of wood log products annually (BMELV, 2012). Germany's leadership in timber and wood-based panel production in Europe is not simply due to its raw wood supplies (EPF, 2014). Germany has adopted a strategy of sustainable forest product usage, and has become a robust industry in the face of uncertainties in the wood sector (IMF, 2014). Forestry and associated wood processing industries provide nearly 1.3 million jobs in Germany, and enjoy an annual turnover of 170 billion euros (BMELV, 2012).

Forest products provide many valuable renewable resources and replace many non-renewable resources, such as fossil fuels. At the same time, they help reduce the atmospheric accumulation of greenhouse gases (GHG). Wood is particularly important for Germany because it is one of the main raw materials produced and processed domestically and represents a key element towards sustainable resource management (Weimar, 2011). Although the supply has fluctuated in recent years (Trømborg et al., 2013), the increasing prices of fossil fuels have caused steadily rising demand for wood resources. These wood resources include industrial wood, industrial residue, and waste wood (Härtl and Knoke, 2014; Schwarzbauer and Stern, 2010). Moreover, because the wood resources used to generate energy can also be transformed into wood-based panel boards, pulp, paper, and wood pellets, the competition for these wood resources has increased significantly.

As part of Germany's effort to reduce its dependence on fossil fuels and nuclear power, it has created subsidies to encourage energy crop production. This has resulted in competition over land use. One possible remedy here is to implement and/or increase the cascade utilization of renewable resources. In response to the challenges facing forest usage, the European Commission adopted a new EU Forest Strategy in 2013. The goal is to use raw wood material in a certain order of priority, according to principles of cascade utilization, while still adhering to the Renewable Energy Directive (AEBIOM et al., 2013). Whereas the supply of fresh wood falls short of demand, cascade utilization can help to reduce deficits. According to Sirkin and Houten (1994), cascade utilization is a method that "optimizes resource utilization through a sequential use of remaining resource quality from previously used commodities and substances." In other words, in the cascading strategy, biomass is used (and reused or recycled) at least once or several times as a product before its end-of-life (e.g., energy). The benefits of a cascading strategy can include expanding the lifespan of biomass use (e.g., particleboard recycling) and maximizing the value extracted from the whole life cycle of biomass product (Geldermann, 2012; Odegard et al., 2012; Sathre and Gustavsson, 2006). However, it may lead to environmental impacts as a result of additional logistical operations, which may compromise any savings attempted through cascade utilization. One ongoing research topic involves assessing the contribution of the entire value chain to sustainable development (Geibler et al., 2010). Figure 1.1 shows the wood flow, from primary resources through the intermediate manufacturer to the wood products manufacturer. In literature, many aspects of life cycle assessment of wood from forests as primary sources to product manufacturers and/or energy conversion have been taken into account. To some extent, the research on cascade utilization of wood also tracks its many uses, including those for chemical purposes, from raw material through power generation at the end of its life cycle. There is, however, scarce research about the material use of wood through cascade utilization. This often complex organizational structure requires more logistical operations and restructuring of value chains. Suitable planning approaches are needed to yield viable production strategies for potential sequential usages of wood throughout the value chain (Figure 1.2). As wood resource operations become more complex, both positive (e.g., reduced fresh wood consumption) and negative (e.g., increased logistics and transport) impacts can be seen.

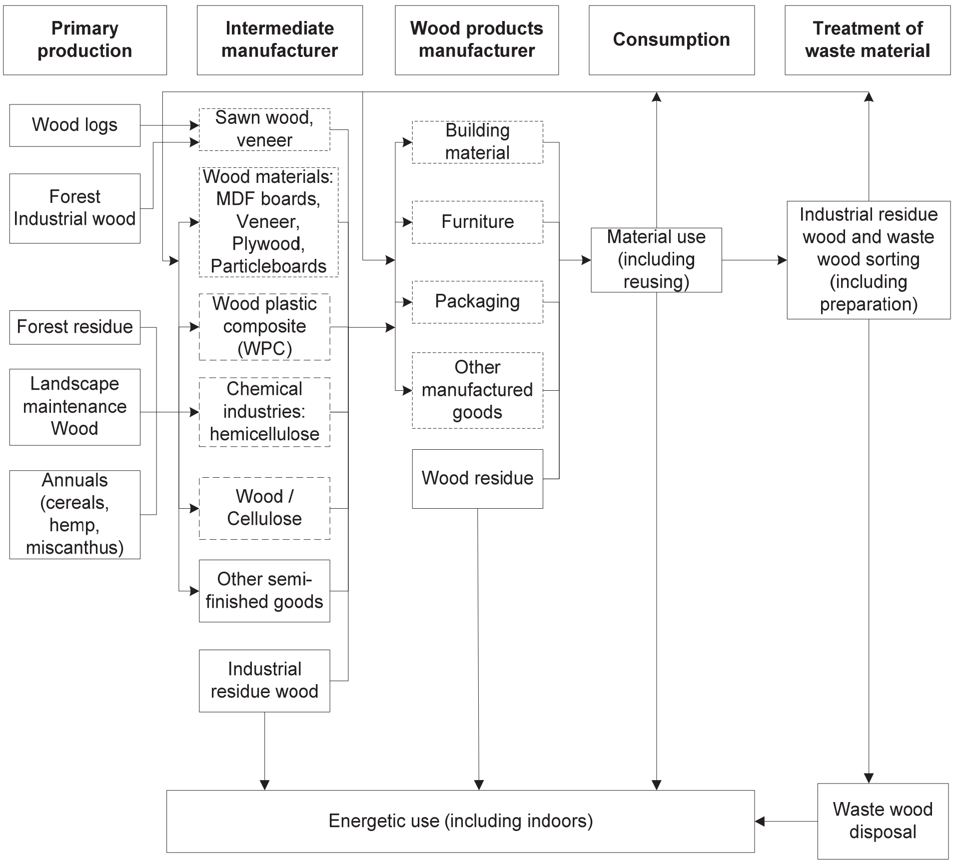

Figure 1.1 Cascade of wood-use (Bienge, 2010)

Several studies have highlighted the benefits of using proper cascade utilization for wood supplies. On the basis of energy and carbon balances, Sathre and Gustavsson (2006) categorized the effects of proper cascade utilization as either direct, substitution, or land use. The direct effects of a cascading network include a down-cycling recovery process and more sustainable consumption. The resulting reduction of demand for non-wood materials and fewer logs appropriated for wood were categorized as substitution and land-use effects, respectively. Rivela et al. (2006) conducted a life cycle assessment for waste wood utilization, in which the potential environmental impacts of a material use of waste wood were compared against its energy conversion. Their study found that waste wood used for materials had a more favorable environmental impact than when it was simply burned. Other studies have found that thorough planning can drastically increase the service life of a wood source. Fraanje (1997), for example, found that pinewood in the Netherlands can potentially have its service life increased from 75 to 350 years if it is successively employed along a chain of material, chemical, and combustion usages. Although cascade utilization may yield some benefits, one must also account for additional complexities, such as increased logistical efforts. Moreover, when substituting materials and creating new product uses, new business partners must become involved in the wood production process.

Quantification of the positive environmental effects and the trade-offs that result from other consequences of cascade utilization, however, remains an open question in both theory and practice. Specifically, the realization of the cascade principle requires additional logistics operations to achieve mass and energy flows between material use, chemical use, and energy use (Figure 1.2), which are all typically allocated to different companies at often distant locations. The positive effects of cascading utilization are contrasted by the environmental impacts from additional logistics processes. These processes bring environmental effects that must be quantified and considered with respect to the overall results of cascading utilization. A sector-by-sector mass flow analysis can quantify resource potentials, cascades, and carbon effects (Mantau, 2014). A wood resource balance helps to analyze the origins of resources, the production of products, and the resulting energy use. The wood flow analysis also integrates all finished products, such as paper and waste paper in the pulp industry, or lumber and panels in the construction, furniture, and packaging industries. Mantau (2014) created a comprehensive sectoral mass flow for 2,194 sawmills, 541 biomass plants, and 1,279 disposal companies in Germany. In his overview, he stated that, “for political action it is important to have a view of the whole system, including the total wood industry, the forest owners, and the disposal companies” (Mantau, 2014). This means that individual companies—which remain separate, but still potentially connected through this integrated wood flow—will need decision support to participate in a cascade utilization that involves changing business partners and work relationships.

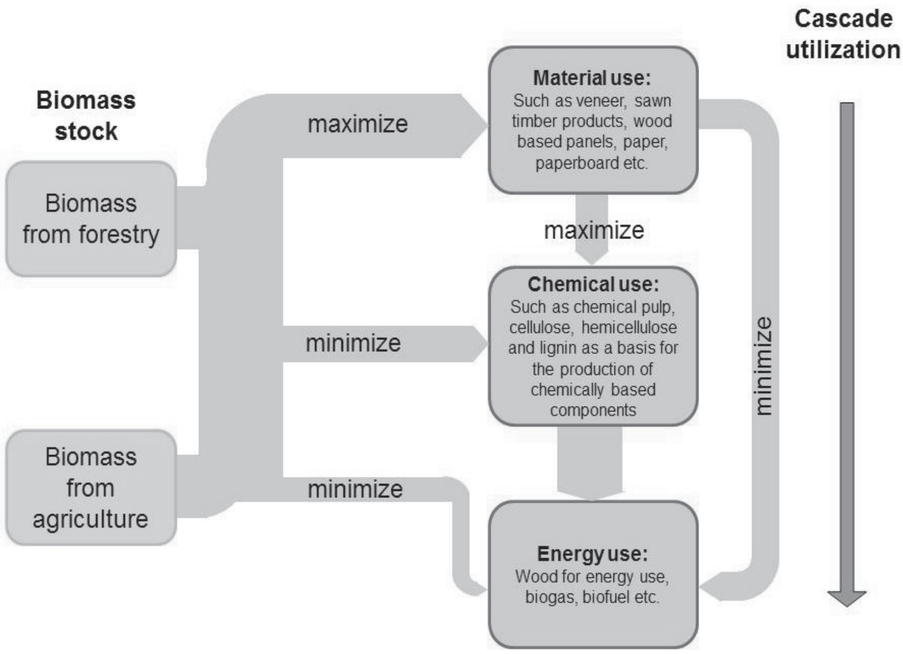

Figure 1.2 Diagram of optimized cascade utilization (arrows represent mass flows; Geldermann, 2012)

Figure 1.3 displays a schematic overview of the wood value chain and the steps within cascade utilization. This overview illustrates how the cascading principle can result in multiple interdependencies. Waste wood (the post-consumer wood product) is processed into a bio-based final product (such as particleboard), and this final product is used at least once more for either materials or energy. One can use a quantitative model, such as mixed integer linear programming (MILP) model, to see how cascade utilization affects different industries. In this context, this dissertation endeavors to answer the following methodological questions:

- How does cascade utilization affect the economic and environmental results for the logistics network for wood products?
- How do various methods to solve a multi-objective optimization help decision makers to obtain better approximations of optimal solutions?

In addition to those inquiries, this work uses LCA to answer the following questions:

- Does cascade utilization of waste wood lead to lower environmental impacts when producing wood-based panel boards, coated paper, and wood pellets in comparison to their production from fresh wood?
- What aspects of the cascading system are decisive for the results desired?

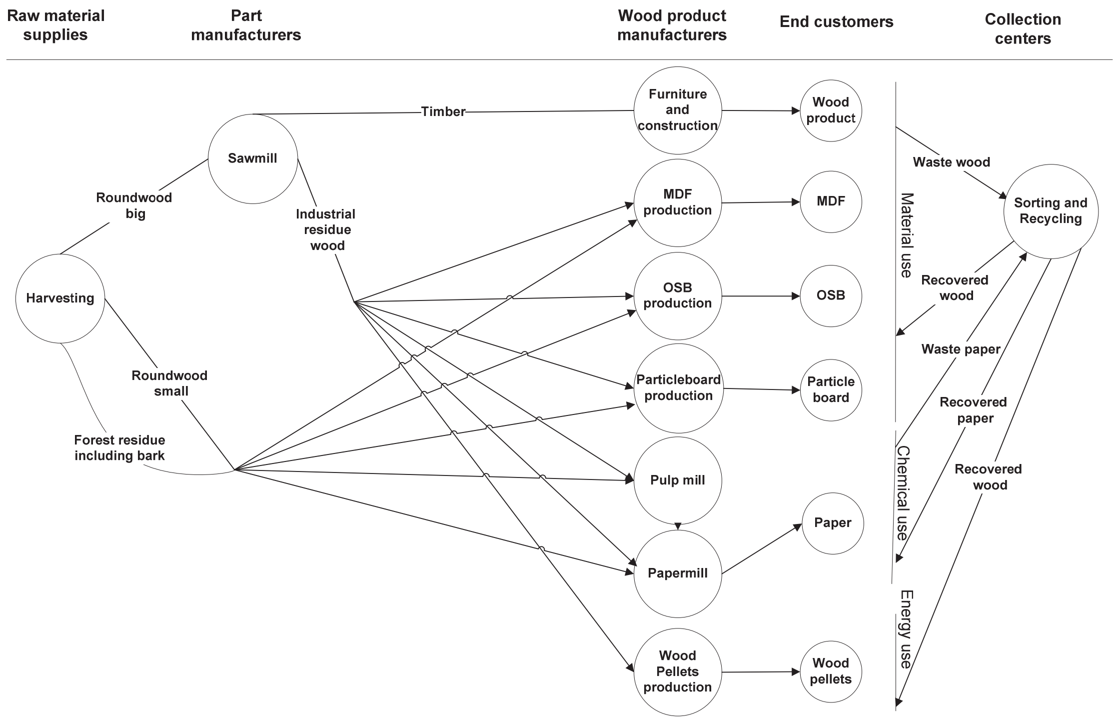

Figure 1.3 General supply chain design of wood flow for wood-based products

Therefore, this dissertation presents and illustrates a quantitative model for the logistics networks resulting from cascade utilization by analyzing two sample case studies. Manufacturing wood products from either fresh wood or waste wood, the wood products considered are medium-density fiberboard (MDF), oriented strand board (OSB), particleboard, coated paper, and wood pellets. The work aims to provide a tool for decision support that allows companies to compare additional economic and environmental effects, in terms of costs and CO_2 equivalents, respectively, produced by the required logistics processes, from different cascade principle implementation options. Decision makers in individual companies or in industrial networks can obtain further insight from this work primarily through its quantitative model to optimize the logistical costs in a logistics network for wood flows in a cascading system, and from its analysis of the associated CO_2 equivalents to measure their global warming potential (GWP) as well. The determination of CO_2 equivalents, representing the most important category for analyzing the environmental impact of climate change, is an important prerequisite for leveraging supply chain decarbonization opportunities. However, other environmental impact categories like land use can also be calculated to investigate further positive (or negative) environmental impacts from the production of wood products through cascade utilization. Specific constraints for wood supply, demand and products characterize the sample case studies presented in this dissertation. The quantitative model developed helps to identify which effects must generally be considered for the evaluation. In order to address these objectives, this thesis is structured as follows:

In Chapter 2 wood as a primary resource for wood products is described. Accordingly, different wood types and their availability in forests are discussed. As the objective of this work is to investigate the material use of post-consumer waste wood, the variety of waste wood and the actual methods of sorting and recycling are presented. In Chapter 3, literature on cascade utilization and logistics network for wood flow is reviewed and classified according to the considered logistical processes and applied quantitative methods. The reviewed literature is mainly focused on the design of a logistics network and the consequences of wood cascading for the economic and environmental consequences. A general definition of a wood supply chain and further information on several supply chain stages is described. Another matter of discussion is the application of Operations Research (OR) in various wood supply chains. Several papers have highlighted the role of mathematical models for planning decisions about transportation, production, and the storage of wood products. The approach presented in this work provides a guide for a self-developed logistics network consisting of suppliers, distributors, and producers. Within these business units, the logistics network for both wood flows from by-product and cascade utilization are illustrated and modeled.

Based on the analyses in Chapters 2 and 3, logistics networks for wood flow from primary resources (fresh wood) and cascade utilization is modeled in Chapter 4. Five wood products—produced from industrial wood logs, by-products and waste wood are considered as sinks: MDF, OSB, particleboard, pulp and paper, and wood pellets.

Based on the models in Chapter 4, reports that provide realistic data on wood availability as well as wood products and their locations are used in Chapters 5 and 6 to apply the decision support system developed to the logistics network problem of wood flow from cascade utilization. Two case studies are investigated to test the consequences of the parameters in a wood flow logistics network cascading system in comparison to a fresh wood scenario. The results and managerial implications are discussed.

In Chapter 7 the findings of this work are summarized and possible applications of the decision support system are described. An outlook on research opportunities concerning the model, the applied methodology, and possible further applications of the approach developed concludes this work.

The model is verified by analyzing its decisions in theoretical test cases (see Appendix A). Modifications of the model are also presented that incorporate: the selling of fresh wood, by-products, and waste wood; advances in sorting methods from the availability of suitable waste wood; and variations in the price of the input material and CO_2 emissions. The set of model modifications presented clearly shows the adaptability of the optimization approach to different planning situations.

2 Wood Resources and their Potential Cascade Uses

This chapter gives a brief description of wood properties, its availability and its potential uses in several sectors. Waste wood utilization as a substitute for primary resource is also a matter of discussion. Finally, the use of five wood products is explained to emphasize the scope of application of the wood products in this work.

2.1 Wood and its application

Wood is a renewable resource and an important energy source for sustainable development (Sathre and Gustavsson, 2006). It is the most widely used material of natural origin which is produced from forests (Werner et al., 2007; Wolf-Crowther et al., 2011). Nowadays, it is produced in many forms, such as sawn wood, wood-based panel board (e.g. particleboard), plywood, and veneer. Wood, in the primary source (forest), is available in various dimensions with different heating values, and densities due to its hygroscopic nature (Werner et al., 2007) which plays an important role for the wood quality. The wood quality can be affected by the growth of mold fungus as well as natural swelling and shrinking movements (Werner et al., 2007). However, it is possible to avoid or postpone the wood quality loss by the production of the wood-based panels such as particleboard. Wood is also a vital material for the production of pulp and paper, and thus plays a significant role in the packaging sector. With regard to sustainable resource management it is considered as one of the main resources manufactured and utilized in Germany (Weimar, 2011). Figure 2.1 illustrates wood products that are derived from round wood (logs). In Germany, the wood supply decreased to 54 million m³ in 2014 compared to 76.7 million m³ in 2007 due to the economic crisis (Destatis, 2015; Trømborg et al., 2013). However, there is an increasing demand for wood resources, including industrial wood, industrial residue wood and waste wood, as an energy source, due to the rising price of the fossil fuel (Härtl and Knoke, 2014; Schwarzbauer and Stern, 2010) and to mitigate the greenhouse gas (GHG) emissions (Mantau et al., 2007). In the following section, the significant utilization potential of wood as a renewable resource in various sectors will be discussed.

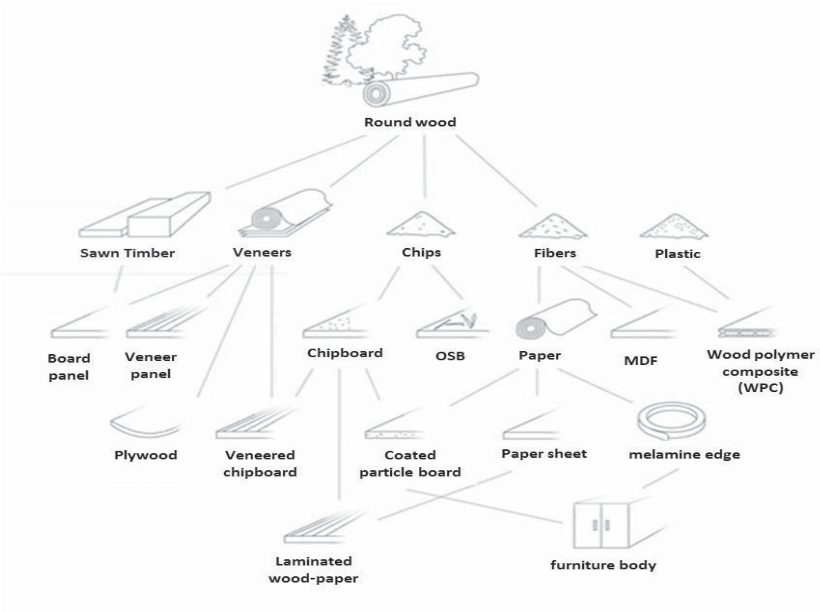

Figure 2.1 Genealogy of wood as a material, adapted from the German Association of Wood Products Industry (VHI, 2014).

2.2 Forest sources in Germany

One-third of Germany is covered by forests (about 11.3 million hectare), which yields more than 53 million m³ of harvested wood log every year (BMELV, 2012). Figure 2.2 illustrates the proportion of forest to land in several areas of Germany. Bavaria has the highest volume of forest with a production of 15.143 million m³ per year; whereas Hamburg has the lowest volume, with 11 million m³ per year. Spruce, pine, beech and oak are the most readily available softwood and hardwood, with utilization rates of 48.2%, 25.3%, 22.6%, and 3.9%, respectively. In Germany, about 43% of forests are owned by private companies, while corporations and states (including federal) own 20% and 35% of forests, respectively (Figure 2.3). In Lower Saxony, the total forest area of 1.16 million hectares ranks the state in third place behind Baden-Wuerttemberg and Bavaria. In total, about 4.5 million m³ wood logs are harvested annually where 59% of the total land areas of Lower Saxony are private corporation forests (Spellmann and Kehr, 2007). The German National Forest Inventory (BWI) defines three categories of wood logs, based on their diameters:

1. Round wood with diameters of more than 40 cm,
2. Round wood with diameters between 20 to 40 cm[1]
3. Industrial wood is comprised of logs that are not supplied to the sawmill industry due to a lack of quality (diameter of less than 20 cm). These logs are supplied directly to the wood-based manufacturing industries.

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[1]The first two categories of wood logs are suitable for timber production and can be supplied to wood cutting industries, such as sawmills.

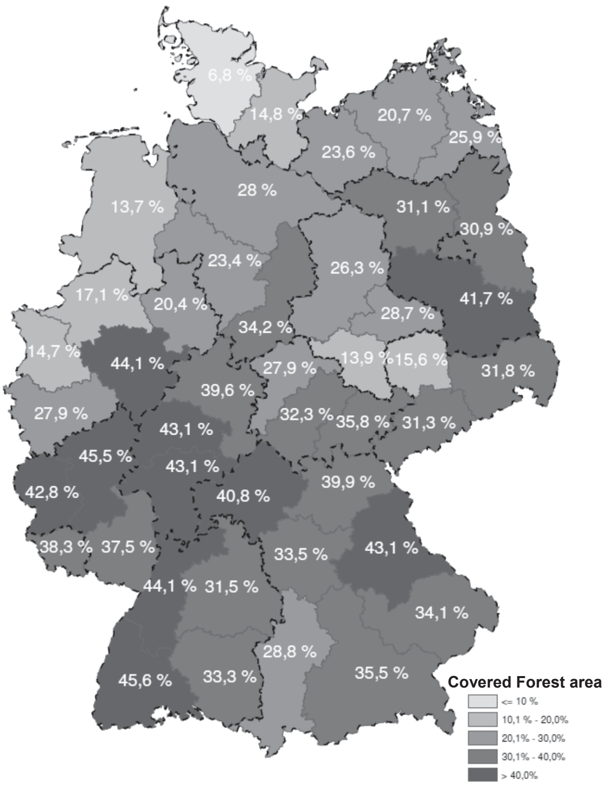

Figure 2.2 The proportion of covered forest area in Germany (Polley and Kroiher, 2006)

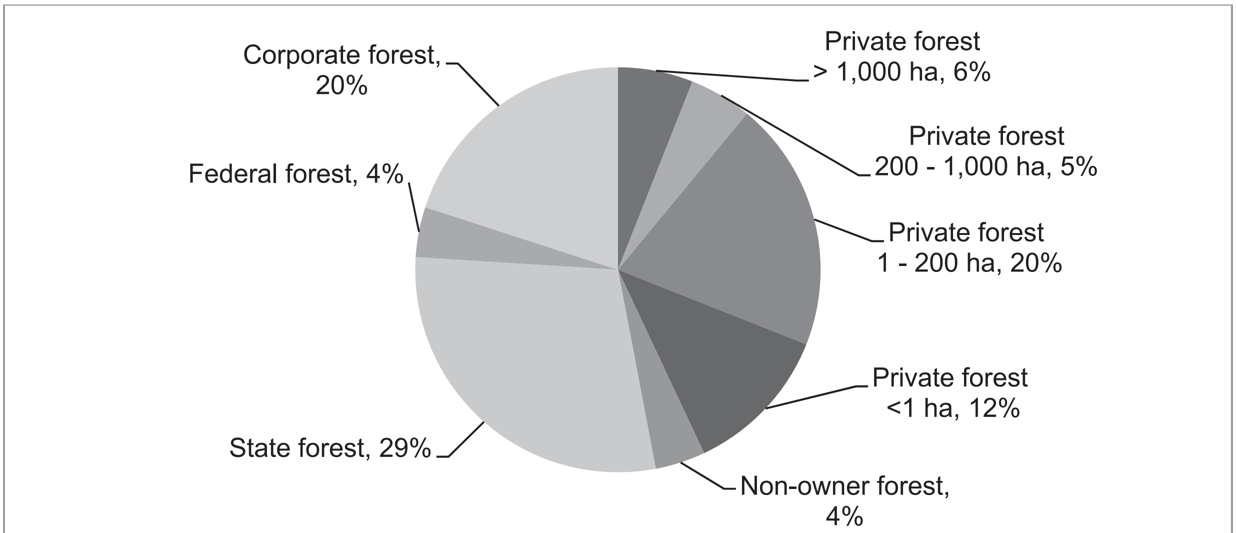

Figure 2.3 Forest ownership in Germany (Polley and Kroiher, 2006)

In Germany, most of the forests today are composed of 60% coniferous forests and around 40% deciduous forests. The top four prevalent tree species are spruce (28%), pine (23%), beech (15%) and oak (10%) (Polley and Kroiher, 2006). Due to wood's anisotropic (different physical properties at different levels of measurement) and inhomogeneous characteristics, its properties vary from tree to tree, as well as within the same log. In one example, Polley and Kroiher (2006) have indicated that softwood such as spruce is available in different qualities (in terms of diameter) throughout Germany. It is the most important economic tree type with a very high supply and growth rate in Germany (Polley and Kroiher, 2006). Spruce is used much more intensively than other tree types. About 50% of total spruce supply is from private sectors. Norway spruce (Picea abies) is the most important forest tree species which has the highest growing stock as well as the largest growing area in Germany (BMELV, 2012; Kölling et al., 2011). The smallest spruce wood log is in Lower Saxony (with a diameter of 45 cm), and the biggest one is in Hessen (with a diameter of 50 cm). Although the target age for the end use is usually from 130 to 140 years (Table 2.1), as a result of the intensive use and enormous storm damage, there are at present relatively little spruce trees and stocks that are older than 120 years. The information about the log diameter is significant due to the fact that it plays a role on the efficiency of the sawing process and therefore economic income of sawmills (see section 3.2.1 on page 51).

Table 2.1 Harvesting rotation years for Spruce (Polley and Kroiher, 2006)

Rotation years for spruce	Region*	Share of the total spruce stock in Germany
165 Years	Lower Saxony	5%
140 Years	Bavaria, Saxony	47%
130 Years	Schleswig-Holstein, Hessen, Rheinland-Pfalz, Baden-Württemberg, Saarland	30%
120 Years	Nordrhein-Westfalen, Saxony-Anhalt, Thüringen	16%
100 Years	Brandenburg	< 1%
80 Years	Mecklenburg-Vorpommern	1%

*The diameter for the wood logs are in average 45 cm for Lower Saxony and Bavaria and 50 cm for Hessen. The information for the diameter of the wood logs for other region is not provided by Polley and Kroiher (2006)

Pine is the second most common tree type in Germany. Despite the decline in area between 1987 and 2002, its supply has risen (Polley and Kroiher, 2006). The regions with the highest proportion of pine are northern Germany and the northern regions of Bavaria. Same as spruce, nearly half of the pines are supplied from private forests. Beech is the third most common tree type in Germany, with a standing wood volume of 583 million m^3 (Polley and Kroiher, 2006), about 10 million m^3 of which is harvested annually (Häusler and Scherer-Lorenzen, 2001). This made Germany the center of beech distribution in Europe and the country with the highest proportion of beech forests in the world (BfN, 1999). Bavaria, Baden-Württenberg and Hessen are the states with largest volumes of beech wood where the standing of wood volume is increased by 25.8% from 1987 to 2002 (BWI, 2014; DFWR, 2008) due to the increase of utilization rate. One fourth of the beech harvested, about 2.6 million m^3, are used by sawmills for timber production and the rest are sold as industrial