Universität für Bodenkultur Wien
University of Natural Resources
and Applied Life Sciences, Vienna

Department of Material Sciences and Process Engineering

Institute of Wood Technology and Renewable Materials

Head of the institute:

Wolfgang Gindl-Altmutter, Univ.Prof. Dipl.-Ing. Dr.nat.techn.

Supervisior:

Univ.Prof. Dipl.-Ing. Dr.nat.techn. Dr.h.c. Alfred Teischinger

Univ.Prof. Mag.rer.soc.oec. Dr.rer.soc.oec. Manfred Gronalt

MODELLING THE MULTI-TIER SOLID HARDWOOD SUPPLY CHAIN

MODELLIERUNG DER MEHRSTUFIGEN LIEFERKETTE VON LAUBMASSIVHOLZ

DI Sebastian Kühle (FH)

Submitted for the Doctoral degree of
Natural Resources and Life Sciences

Vienna, February 2020

Acknowledgements

First and foremost, I wish to thank my supervisors Prof. Alfred Teischinger and Prof. Manfred Gronalt for their support and guidance during my PhD studies, as well as for giving me the opportunity to carry out my thesis in their institutes.

My thesis was conducted with the support of hardwood companies. I want to acknowledge them and the Austrian Federal Ministry of Science, Research and Economy for financing my project in the framework of the PhD School DokIn Holz.

Special thanks goes to all my former colleagues for their help and support in the daily work, for creating such a pleasant working atmosphere and the nice moments we all shared together.

I want to thank Momo and Adriana for their sincere words to finish the thesis in times of climate crisis, even if it was a huge dichotomy for me until the end.

die Leute, die ich wegen der These treffen konnte

In the end, I want to thank all my friends for their support and understanding, especially in the work-intensive times. Special gratitude goes to my family, who were a great support during my way of life. Thank you.

Abstract

This doctoral thesis was developed within the framework of the doctoral initiative "Wood - Value-added material with a future" (DokIn'Holz).

Based on a literature study and evaluation of a large number of hardwood initiatives and projects in Europe, the aim of this PhD thesis was to identify and model new approaches to hardwood process chains for material use and to provide data on the solid hardwood production network. In contrast to the different process chains for softwood with a focus on load-bearing and bracing purposes in construction, the use of hardwood is much more fragmented and complex. In order to design an efficient production network for hardwoods, which is characterised by diversity and complexity, appropriate cross-company planning methods have to be developed, which contribute to improving the competitive position of individual actors as well as the network as a whole. Different approaches of production planning such as mass customization and supply chain management have been used to identify, model and evaluate possibilities for professionalization and thus to identify new ways of using hardwoods for companies in the production network.

For the introduction and the reasoning behind this paper on hardwoods, background and motivation are highlighted first. In order to understand the scientific context that provides the framework for this work, the problem description and related works are discussed. Then, the methods used are presented. Finally, the results of the work are presented and discussed what they mean for the multi-tier hardwood supply chain in terms of product, technology and production processes, as well as for supply chain design and production management with mass customisation.

Kurzfassung

Diese Doktorarbeit ist im Rahmen der Doktoratsinitiative „Holz – Mehrwertstoff mit Zukunft“ (DokIn’Holz) entstanden.

Das Ziel dieser Doktorarbeit war es, basierend auf einer Literaturstudie und Bewertung einer Vielzahl von Laubholzinitiativen und Projekten in Europa, neue Ansätze für Laubholzprozessketten für die stoffliche Nutzung zu finden und zu modellieren sowie Daten über das Produktionsnetzwerk zur Verfügung zu stellen. Im Gegensatz zu den verschiedenen Prozessketten Nadelholz mit einer Ausrichtung auf tragende und aussteifende Zwecke im Bauwesen, ist die Nutzung von Laubholz wesentlich fragmentierter und komplexer. Für die Gestaltung eines effizienten Produktionsnetzwerkes Laubholz, das geprägt ist von Vielfalt und Komplexität, müssen entsprechende unternehmensübergreifende Planungsmethoden entwickelt werden, die sowohl zur Verbesserung der Wettbewerbsposition einzelner Akteure wie des gesamten Netzwerks beitragen. Durch verschiedene Ansätze der Produktionsplanung wie Mass Customization und Supply Chain Management sollen Möglichkeiten einer Professionalisierung aufgezeigt, modelliert und hinsichtlich ihrer Umsetzung bewertet und damit neue Wege der Laubholznutzung für Unternehmen im Produktionsnetzwerk aufgezeigt werden.

Für die Hinführung und den Grund dieser Arbeit zu Laubholz werden zu allererst Hintergrund und Motivation beleuchtet. Um den wissenschaftlichen Kontext, der die Rahmenbedingungen dieser Arbeit schafft, zu vergegenwärtigen, werden die Problembeschreibung und verwandten Arbeiten behandelt. Anschließend werden die verwendeten Methoden dargestellt. Zuletzt werden die Ergebnisse präsentiert, die im Zuge der Arbeit entstanden sind und diskutiert was sie für die mehrstufige Laubholzlieferkette bedeuten in Bezug auf Produkt, Technologie und Produktionsprozesse sowie für Lieferkettendesign und Produktionsmanagement mit Mass Customization.

Keywords

Facility Location, Hardwood Laminated Wood Product, Optimisation Model, Postponement, Process Flow, Process-Technology Matrix, Quality Function Deployment, Supply Chain Management, Supply Network Design, Value Stream Mapping

List of publications

I. Kühle, S; Teischinger, A; Gronalt, M (2016): Structure analysis of a production network by means of quality function development and values stream mapping.
World Conference on Timber Engineering (WCTE 2016). Vienna, August 22-25, 2016.
In: J. Eberhardsteiner, W. Winter, A. Fadai, M. Pöll, (Eds), CD-ROM Proceedings of the World Conference on Timber Engineering (WCTE 2016); ISBN: 978-3-903039-00-1

II. Kühle, S; Teischinger, A; Gronalt, M (2019a): Connecting Product Design, Process, and Technology Decisions to Strengthen the Solid Hardwood Business with a Multi-Step Quality Function Deployment Approach. Bioresources 14(1): 2229-2255. DOI: 10.15376/biores.14.1.2229-2255.

III. Kühle, S; Teischinger, A; Gronalt, M (2019b): Optimal location of laminated beech production plants within the solid hardwood supply network in Austria. Silva Fennica vol. 53 no. 3 article id10074. 22 p. DOI: 10.14214/sf.10074.

IV. Kühle, S; Teischinger, A; Gronalt, M (2019c): Form-based postponement in the solid hardwood supply network. Cogent Business & Management. DOI: 10.1080/23311975.2019.1701887.

Contents

1. Background and Motivation

Forest as system element of the earth is attributed with essential economical, ecological and social functions. It is a renewable resource which provides timber and non-timber products, it is a source of health with storing carbon, building space for free time and recreation, it prevents soil erosion, it is the habitats for plants and animals, it creates jobs and economic value. Forest fulfils multi-function for humans, and we depend on it.

"However, forests are under pressure. Storms, fires, pests and beetles are expected to damage forests more frequently and more intensely as a result of climate change" in Europe (San-Miguel-Ayanz et al. 2016). The intensives effects on the forest are traced back to the past management practices which lead to climate sensitive forest in the present and will likely continue in the future (Seidl et al. 2011). Forest manager counteract the progress with a closer to nature forest strategy. In central Europe, this results partly in a changing forest stock share. Pure broadleaved trees and mixed areas have increased and pure softwood stands have decreased (Ministerial Conference on the Protection of Forests in Europe 2015).

In general, wood processing and the associated wood process chains are structured according to the raw material resources such as soft-wood processing (coniferous wood species) and hard-wood processing (non-coniferous, broad leaved species). In terms of processing sites, primary wood processing, such as sawmills, is located close to forest resources, while downstream processing firms are located close to primary wood processing or close to the end customer. The commercially used broad-leaved wood species comprise a much higher spectrum of wood species than the coniferous wood species. Also, the spectrum of wood properties of the broad-leaved species is much broader than with softwood (Grosser 2011). Wood density is one of the leading indicators for the various mechanical wood properties (Niemz and Sonderegger 2017), despite the many other physical and chemical properties and the appearance of colour and texture, which is important property for the use of wood in appearance applications.

The various hardwood species comprise a broad spectrum of wood density, but in industrial wood utilizations the common broad-leaved wood species are frequently referred to as “hardwoods” even including such species with lower density. Therefore, in the current thesis, the term “hardwood” is still used, and when necessary, a specific hardwood species (e.g. beech (*Fagus sylvatica*) or oak (*Quercus sp.)* is addressed (Figure 1).

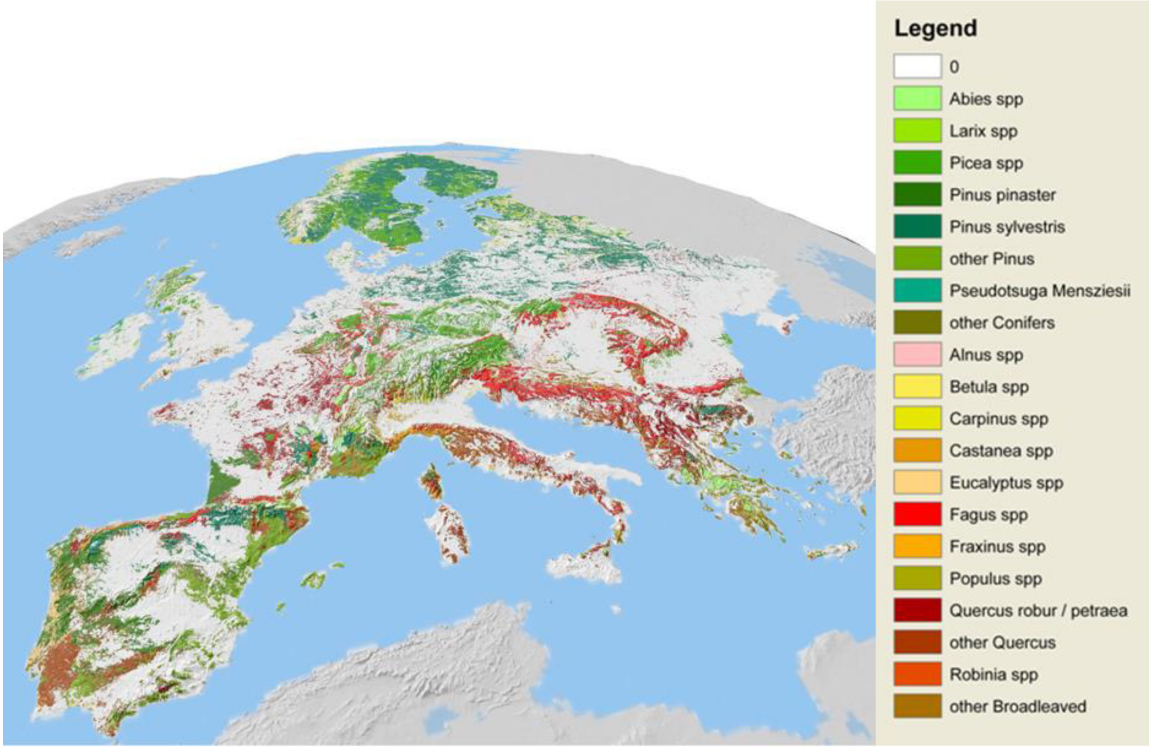


Figure 1: Distribution of tree species in Europe (Brus et al. 2011 und EFI). Presented are the different wood species in Europe, whereas the green areas represent the softwoods and the red-brownish-yellowish areas represent the broad-leaved species.

Based on the developments in the forest and in the composition of resources described above as well as the challenges associated with them, this work deals with hardwoods in order to identify potentials and utilisation concepts. To highlight the relevance of the topic, the European Commission supports the European Hardwood Innovation Alliance program (EHIA) (2016 to 2026), which pools the capacities of the scientific hardwood community to develop value-adding hardwood use and create value based on the unique hardwood resource within the European Union.

The growing stock of broadleaved tree species amounts to 15.0 billion m³ in European forests. The stem volume of living trees is evenly distributed between broadleaved and coniferous tree species in almost all regions with the exception of the North Europe region where around 75% of growing stock is coniferous (Ministerial Conference on the Protection of Forests in Europe 2015). However, European forests contain 43% hardwoods.

These areas and quantities result in an annual increment of 849 million m³ (721 million m³ for EU 28) and an annual timber harvest of 582 million m³ (458 million m³ for EU 28), of which 150 million m³ are hardwoods. Of the total harvest, industrial roundwood makes up 56%, fuel wood 23% and saw logs only 21% (Teischinger 2019).

A detailed hardwood study in Switzerland (Lüthi 2009), the Gülzow Fachgespräche (Anon. 2012) and the detailed hardwood study in North Rhine-Westphalia in Germany (Redmann et al. 2015) document the subject of hardwood, hardwood processing and current projects on hardwood. These are extensive studies, but they may only be the beginning, as there is still a lot of potential for an increasing value stream in these topics.

The business activities in the hardwood industry include resource management, harvesting, logistic and manufacturing operations, distribution of products as well as sales and marketing executed individually by companies. But they are interdependent and consequently a decision made in one area of business has subsequent effects on the others.

To created greater values throughout the transformation process from raw materials to the products, these activities need to be managed and coordinated in order to meet the needs of the consumers. Non-managed and uncoordinated decisions can lead to significant economic costs. This value chain-based thinking helps decision-makers focus on the business processes and coordination as a whole (D'Amours et al. 2017).

Most authors share the objective of minimize costs in the inter-company supply chain between companies with given demand but there are also authors who support the objective of value maximization (Kannegiesser 2008).

Supply chain management supports production and sales decisions in the direction of cross-departmental and cross-company business processes. Supply chain management is based on insights into the bullwhip effect. In the 1950s, the bullwhip effect was observed by scientists at the Massachusetts Institute of Technology. It points to the phenomenon that small changes in consumer demand led to significant fluctuations in production and inventory levels in the subsequent steps of the retailer and manufacturer in the supply chain, resulting in avoidable costs. The main causes of the bullwhip are delays in information and material flows between supply chain actors (Kannegiesser 2008).

For the classification of time and business activity planning the supply chain planning matrix provides an integrated management framework by planning horizon and supply chain process (Rohde et al. 2000, Figure 2). Strategic decisions relate to facility location or distribution center problems. Also called strategic network planning or network design. Tactical decisions are related to planning of quantities in sales, production and procurement. Short-term decisions refer, for example, to the planning of production on a daily basis.

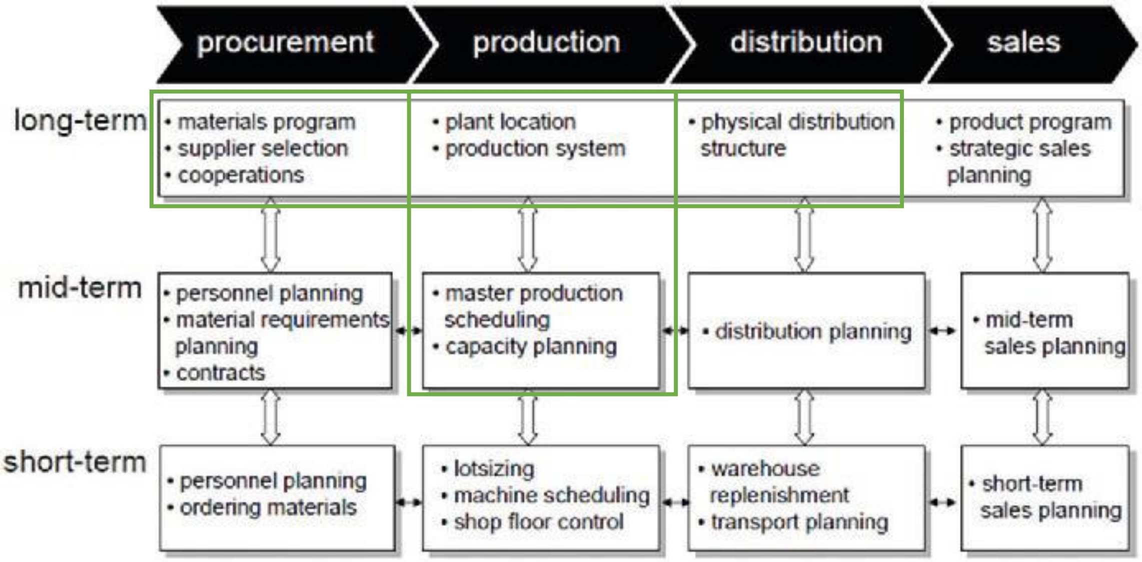


Figure 2: Supply chain planning matrix (Fleischmann et al. 2002). Marked in green are the areas that this work looks at more closely for the production network for hardwood products. The areas of plant location, production systems and capacity planning are dealt with directly. Related topics are also covered by the models or the results such as supplier selection and physical distribution structure.

Santa-Eulalia et al. (2011) provide a detailed version of the supply chain planning matrix for the forst- and wood-based sector. Also, they combined supply chain processes on the horizontal axis or aggregated planning horizons on the vertical axis.

In the last twenty years, new innovative value chains of value-adding raw materials and products have been initiated and partly established for hardwoods. They focus on new approaches of further processing wood products using different wood qualities as well as by-products of the primary processing and special products based on the unique chemical or physical properties of hardwoods. Nowadays, products out of hardwood resources can be found in all areas of civil life with specific shares (Krackler et al. 2011; Verkasalo et al. 2017, Figure 3). The main assortments are fuel wood, industrial roundwood and saw log. For stem wood for example, there is an increasing interest in hardwood as a raw material for building products as high strength load bearing components (Torno et al. 2013; Espinoza and Buehlmann 2018). Currently, solid hardwood based products are mainly used in appearance-based applications such as furniture, flooring, and interior design (Luppold and Bumgardner 2004). A comprehensive survey of hardwood application as solid wood and composites is provided by Krackler et al. (Krackler et al. 2010, Krackler et al. 2011).

Resources	Solid Wood Based Industry	Industrial Roundwood based Industry	Energy & Heat Utilisation	End Consumer Needs
• Beech, maple, ash, oak, chestnut,...	• Consumer goods • Cladding • Stairs • Flooring • Furniture • Boards • Automotive	• Chemicals • Consumer goods (process) • Fuel & Gas • Pharmaceuticals • Pulp & Paper	• Chips & Pellets • Firewood	• Clothing • Education • Housing • Leisure • Medicine • Mobility

Figure 3: Hardwood resource types and areas of application for the products.

Hardwood flow

In Europe, the proportion of the forests is slowly shifting from coniferous to more mixed and deciduous forests, and as a result the wood-based supply chain is also fragmented as there are new areas of application for hardwoods. Overall, the value chain is becoming more complex. Technological improvements have an impact on what type of wood is suitable for various uses. Adaptation of processing technologies to the characteristic properties of hardwoods increases the access to more efficient material yield and value creation. Figure 4 shows an overview of a general hardwood material flow chart. Hardwood species are exemplarily written to the individual material flows. Presented are the more traditional sectors such as sawmill, veneer and panel industries as well as the modern and more innovative sectors which is connected to the pulp and fibre manufacturers or exists alone as a biorefinery. Biorefinery products can be used as biopolymers, biomaterials or biofuels.

In addition to the main material flows of fuel wood, industrial roundwood and stem wood, there are also co- and by product flows, which are raw material for other industries, such as chips from the sawmill industry for the panel industry or by-products from the paper and panel industry for the generation of heat and energy. At the end-of-life phase of products, recover wood or paper flows occur, which are used as raw materials for industries or are used to generate energy and heat.

Closing loops will become a more earnest endeavor, as the pressures mount to use resources more efficiently and to eliminate waste; this will drive new value chain partnerships within the tradition and modern hardwood industries.

This thesis focuses on solid hardwood wood sector which has as focal facility the hardwood sawmills. It is an inhomogeneous business sector within the forest- and wood-based industry. It consists primarily of small to medium-sized companies and even is split into further specialists such as beech-wood and oak-wood processing mills

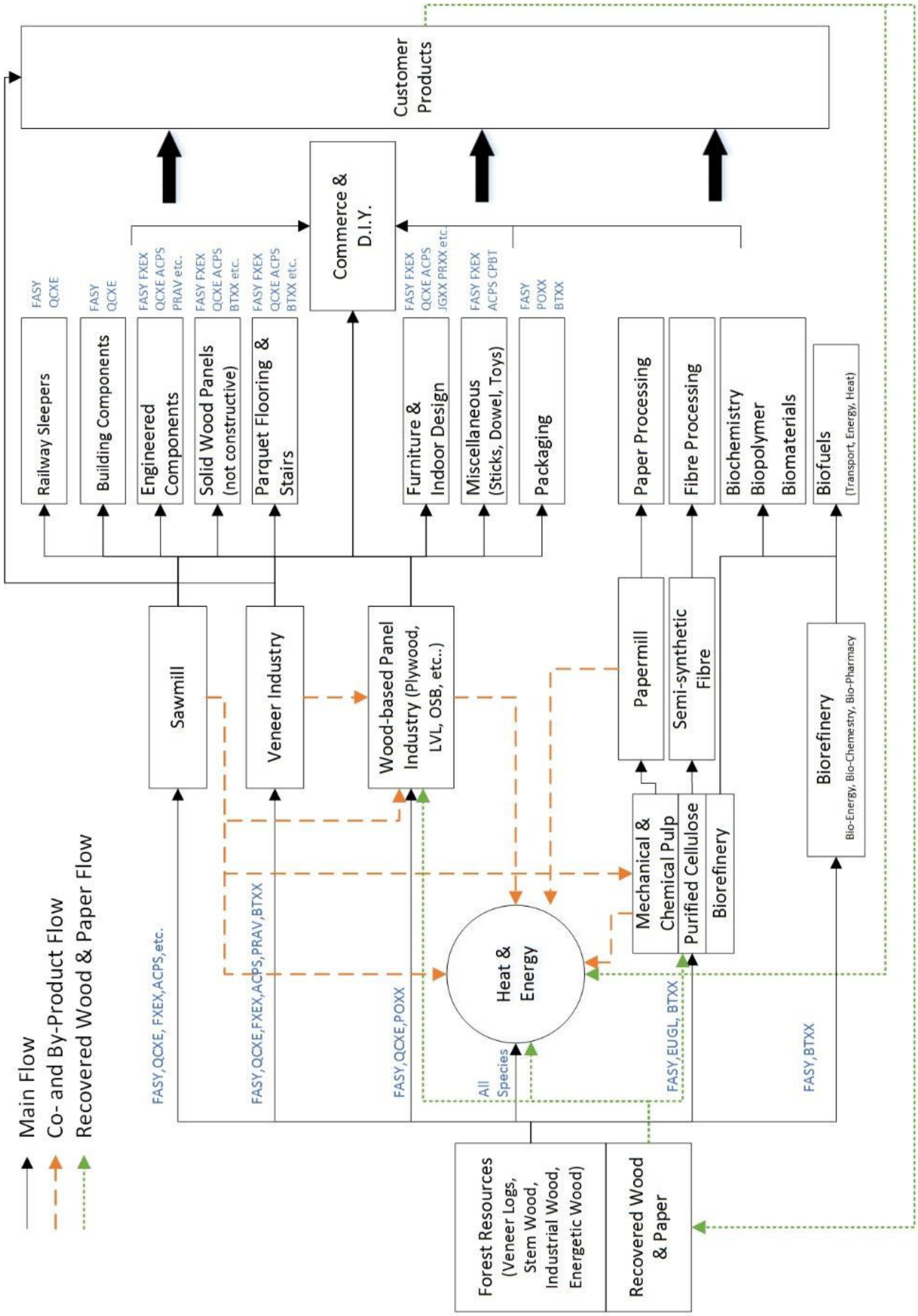


Figure 4: The *Main Flow* shows the allocation of hardwood resources utilization to main products. *The Co-and By-Product Flow* results from the diverse character of wood-based resources. The *Recovered Wood and Paper Flow* is the end-of life flow of hardwood-based products according to a cascading usage. Acronyms of wood species according to EN 13556 (Kühle and Teischinger (2017), adopted from Suckling (2011)).

The utilisation of the renewable resource hardwood is a transdisciplinary topic. Especially when the multi-level supply chain is considered. Therefore, the disciplines wood technology and wood industry production management are applied in this thesis.

For the scientific work it was assumed that with the development of a cross-company analysis method and by modelling the multi-stage hardwood chain, supply chain management can be used to identify potentials along the supply chain and for the respective actors.

Based on this assumption, the dissertation contains four scientific articles dealing with specific aspects to be considered in these topics.

Paper I: Kühle et al. (2019a) investigates the interplay of product architecture, manufacturing processes and dependent technology along a multi-tier supply chain.

Paper II: Kühle et al. (2016) focuses on the aspect of quantitative information providing within the multi-tier supply chain as additional input to the paper before.

Paper III: Kühle et al. (2019b) examines the strategic planning of a of future laminated beech wood supply network (LBWSN) design.

Paper IV: Kühle et al. (2019c) studies a more flexible beech wood supply network based on form postponement.

In the next section, the problem description of the thesis and related work is presented. It is followed by the description of the methodologies which are used in the individual papers. Then, the results and the discussion are presented. At the end, the conclusion is presented with an outlook.

2. Problem Description and Related Work

In the following, the challenges considered in this thesis will be described in more detail and the relevant literature will be presented that illustrate the interdisciplinary approach of wood technology, product development and quality management as well as supply chain management in order to analyse the topic of the multi-tier hardwood production network and its challenges as well as to point out planning possibilities.

2.1. Challenges of the hardwood sector and approach of the thesis

For the quantitative use of hardwoods, for example in the German-speaking countries of Europe, historical data shows that utility of hardwood as industrial roundwood and energy wood develops progressively. In contrast to that, hardwood lumber is decreasing. Data from 1992 to 2017, provided by FAO, show an exemplary utilisation collapse up 30% for Germany, Austria or Switzerland bevor and after the global economic crisis in 2007 (FAOSTAT, Figure 5). Between 1995 and 2013, there is a decreased production of secondary hardwood products in hardwood consuming countries with high per capita (Luppold and Baumgardner 2015,). Figure 6 also represents such a trend up to 2017.

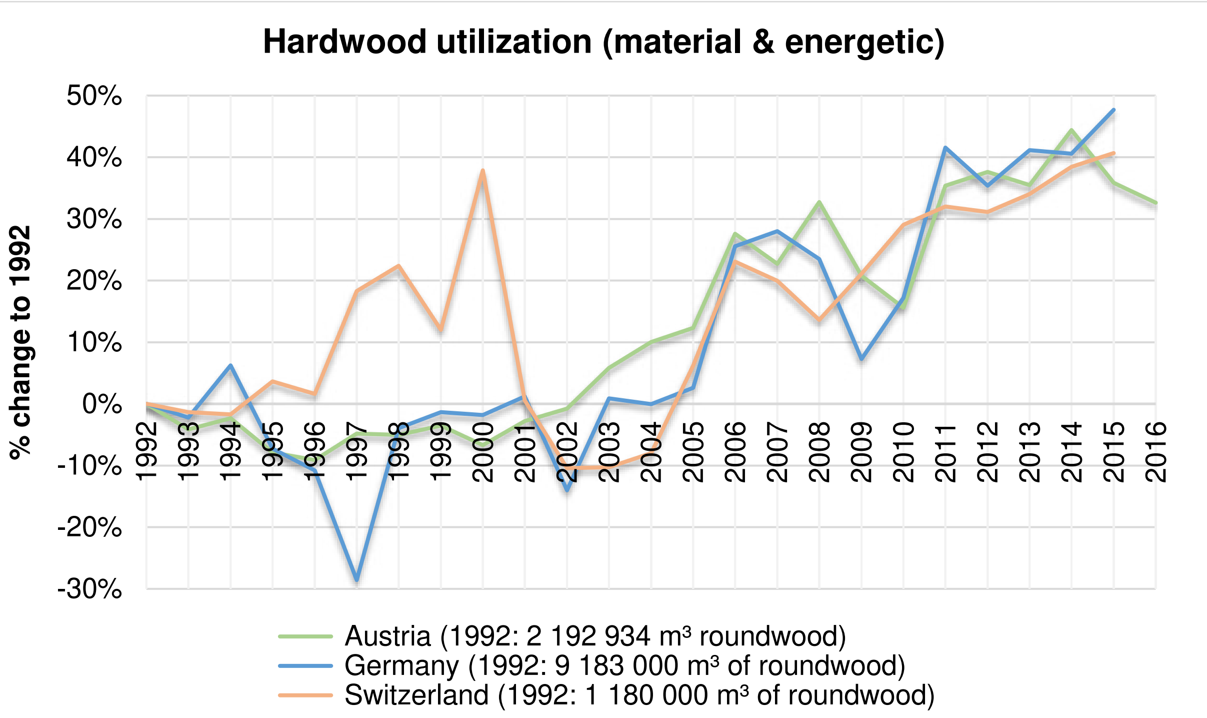


Figure 5: The hardwood utilization is presented for Austria, Germany and Switzerland. There is a trend of more hardwood resources utilization after the time span of 2002 to 2004 for material and energetic use (FAOSTAT).

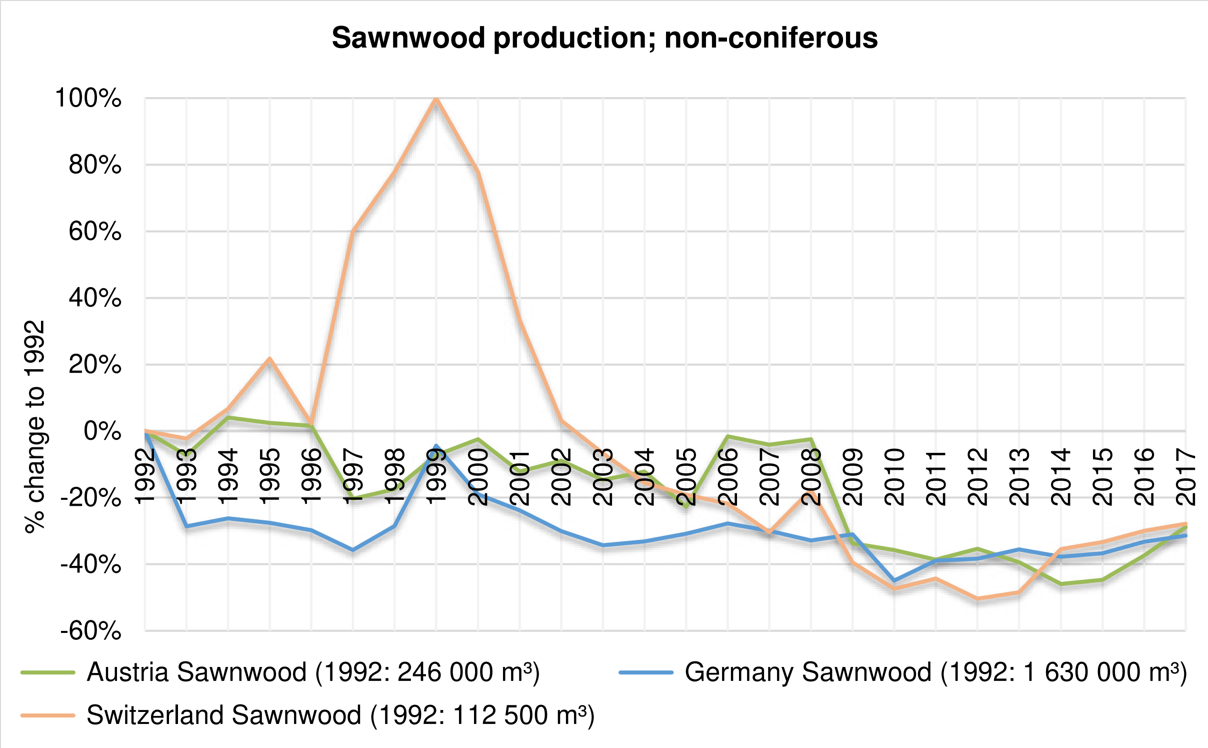


Figure 6: The production of sawn wood for non-coniferous is presented for Austria, Germany and Switzerland. The diagram shows a negative trend at all, but an improvement is visible in the last several years (FAOSTAT).

In general, it can be said that wood processing in Europe is very strongly focused on coniferous wood and most production facilities are designed for coniferous roundwood processing. Hardwoods are increasing in Central Europe and the quantity of hardwood sawn products is decreasing. Currently, the main flow of resources streams directly from the forest into the energy and heat utilisation. This results in the current state of hardwood industrial processing and the associated challenges such as to develop sustainable and value-adding utilisation concepts for the diverse range of hardwoods for main, co- and by-material flows. The implementations of new utilization concepts are lacking. Thus, the utilisation of hardwoods as energetic resource is progressively rising because it is be seen as an easy and profitable solution for unused assortments (Krackler et al. 2011).

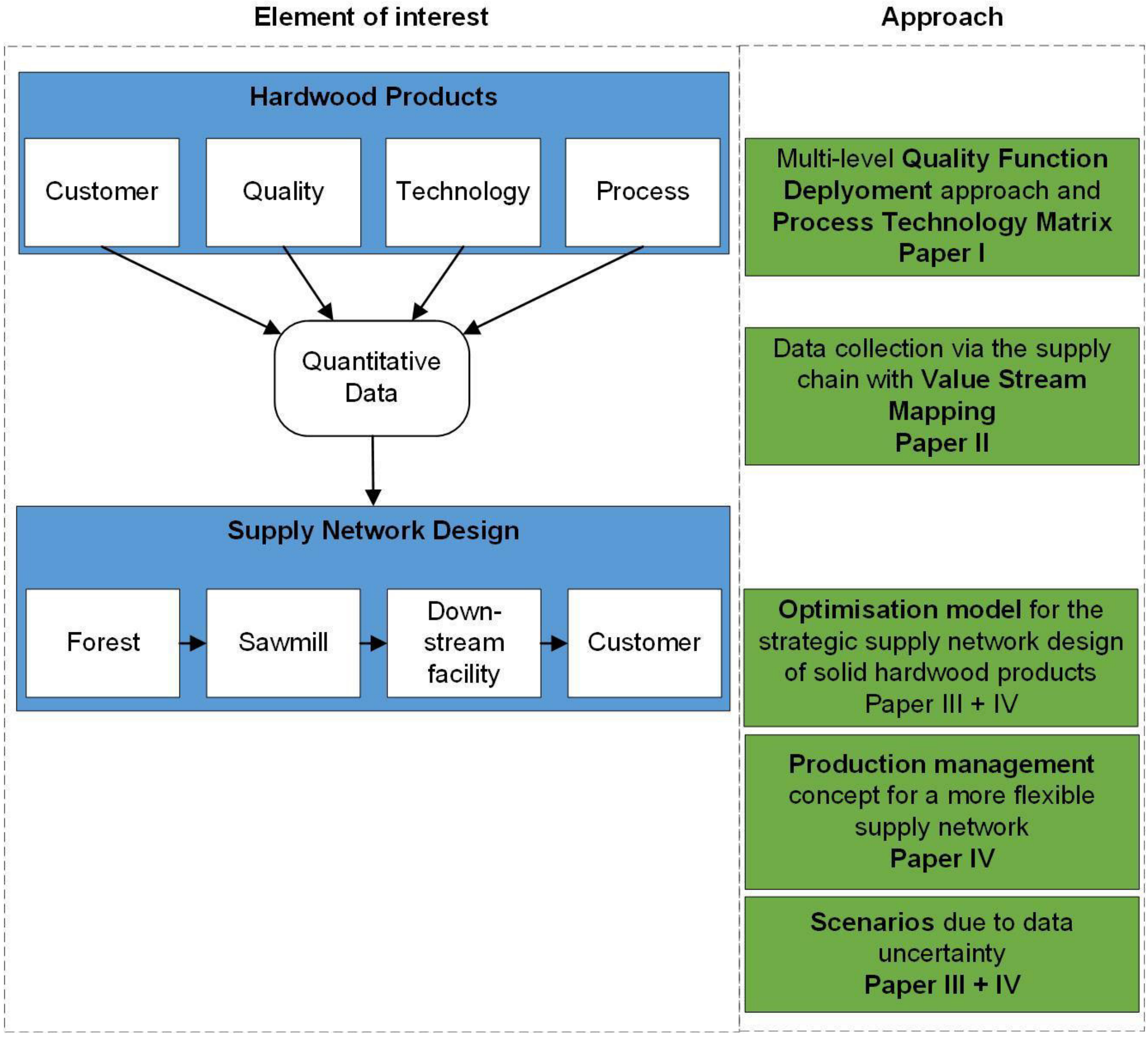
Few data is available for the use of hardwood assortments amounts and their utilisation, production capacities or locations, demand quantities or other key values for planning tools to support decisions related to supply chain management. The demand quantities for new hardwood products are unclear, thus the production capacities of the production plants can be dimensioned, for example. Also, industry-driven innovations are missing which are focused on hardwood supply chain or products (Bollmus et al. 2017, Teischinger 2019).

Technical issues such as gluing and grading are underdeveloped and need to be studied as well as drying of hardwoods. Drying processes have a higher cycle time and consume more energy mostly due to the more complex anatomical structure and higher density (Wilhelms et al. 2017). Thus currently, production cost result for hardwood products which have a negative impact on the economic feasibility of hardwood construction products.

The question of raw material availability generally arises for all raw materials. For renewable raw materials a seasonality has to be considered, which can lead to raw material limitations. For hardwoods it can be said that there are restrictions on felling per year. For example in Austria, regulations signify that all hardwoods used as timber should be harvested during the dormant time. Otherwise, the buyer may refuse to accept roundwood harvested earlier (Österreichische Holzhandelsusancen 2006). In practice, deviations may occur, such as when fast processing and transport to the sawmill is ensured. In the case of hardwoods, the winter half-year is primarily used, starting in September, as the risk of storage and transport damage to hardwoods is significantly reduced in the cooler months of the year.

The above-mentioned framework conditions and challenges, such as the lack of hardwood concepts, the increased use in the energy sector and the lack of information along the hardwood supply chain, make it necessary to examine the production network itself. There are several challenges and issues that need to be addressed with individual approaches (Fi gure 7).

The element of interest is in general the supply chains of solid hardwood products which is studied with the multi-level Quality Function Deployment (QFD) and the Process-Technology Matrix (PTM). A further focus is on the provision of data on production processes within the network with the various players. An approach with quantitative data collection using Value Stream Mapping (VSM) will provide the required data. The last element of interest is the supply network design (SND) of the solid hardwood sector. Here, it includes forest departments, sawmills, downstream facilities and customers. The SND is studied with an optimisation model for the strategic planning of a solid hardwood network and a production management concept is provided for a more flexible supply network. Finally, scenarios are used due to data uncertainty.



Fi gure 7: Overview of the structure of the thesis. The elements of interest are presented (blue) with the corresponding approaches (green).

2.2. Related work to the individual approaches

2.2.1. Multi-step Quality Function Deployment approach and Process Technology

One way to manage the decline in production capacities and increase value is to develop hardwood products for new markets. Dominated by optical applications, stakeholders in the hardwood sector are increasingly interested in hardwood as a raw material for structural building products such as veneer laminated timber, glued laminated timber (GLT) or innovative new products (Luppold and Bumgardner, 2004; Aicher and Ohnesorge, 2011; Hübner, 2014; Ehrhart et al., 2016; Grabner et al., 2016; Verkasalo, 2017). Although there are national technical approvals (e.g. in Germany), there is no fully established industrial infrastructure to manufacture these products in a supply chain from forest to manufacturing companies to customers.

The solid hardwood industry's product process portfolio for existing and new products is demanding and complex because they must be adapted to the variability of individual wood species. For new products this means a great deal of effort, as little is known about product-process-settings. In order to narrow this gap and tackle the presented challenge, a systematic approach to disclose processing opportunities is required. Product architecture, production processes and production technologies have to be considered within one analytical framework (Figure 8). Manufacturing systems must match the specific product design requirements. These requirements change from product to product.

Kühle et al. (2019a) evolves a conceptual framework for a methodology to disaggregate solid hardwood products to their physical blocks, functions, processes and dependent technologies to provide and visualize information as well as specific data systematically for a multi-level supply chain.

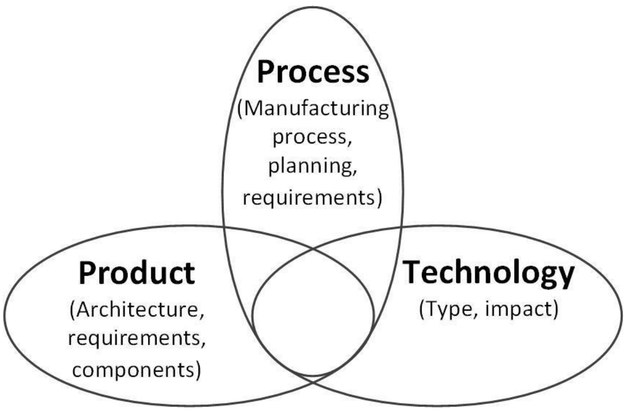


Figure 8: The interlinked parameter product, process and technology are represented with further included aspects. The intersections show the links between two or all three aspects.

The product designs of products and manufacturing processes is strongly interconnected, as confirmed by the product process matrix of Hayes and Wheelwright (1979). The product architecture has an essential influence on the manufacturing. It is related to the structure and components of the product, which are a synergy of a physical product part and an intangible product part such as services or supplier related characteristics (Toivonen 2012). Appropriate selection and optimisation of process chains is essential for product quality, process performance, and production efficiency (Thompson et al. 2015).

For hardwood, single manufacturing processes must synchronize to the whole manufacturing process chain as well as to the depending technology. Due to the variable properties of the raw material, fixed and controlled manufacturing concepts with defined production processes and associated technologies are required, so that e.g. the wood moisture in the downstream processes is well controlled for a high and stable product quality. Available technology has an impact on product architecture, possible process chains as well as firm performance (Lin and Chang 2015).

In order to obtain the mentioned missing information about the supply chain, the product, the manufacturing processes or the technology, there are works that look at individual aspects. With the "Balanced Scorecard" firm strategies are translated with a top-down approach and separates the strategies into individual perspectives like the customer perspective or internal process perspective. Performance indicators are developed and gathered to a scorecard. The measured values for the performance indicators show the degree of fulfilment (Kaplan and Norton 2007; Bigliardi and Bottani 2010). The methodology is beneficial for benchmarking manufacturing companies and divisions. But, the individual character of the developed performance indicators can limit the comparison of firms and divisions (Westlund, Furness-Lindén 2010).

Another framework to identify, design and assess the performance of a supply chain is the Supply Chain Operation Reference Model (SCOR-Model (Supply Chain Council 2008)). For the several supply chain actors, it focuses on the six business processes plan, source, make, deliver, return and enable. The top-down approach breaks these processes down in sub-processes. For each process, it can reach a three-level process detail. Schnetzler et al. (2007) applied the SCOR-Model on national level to provide a communication tool while Audy et al. (2012) analysed and compared international forest-based supply chains.

To visualize, analyze and optimise the product´s manufacturing life cycle, Value Stream Mapping would be a suitable tool. The considered value stream includes the value adding (internal production) and non-value adding (purchase, order and supply) activities that are required to bring a product from raw material through delivery to the customer. VSM can provide information about product manufacturing in combination with technology selection and specific values about manufacturing performance. After the analysis of the processes and the development of a first VSM map, the data would be a quantity base for further optimisation or simulation. With the Dynamic VSM approach, also the disadvantageous static system can be overcome (Dos Santos, J. G. et al. 2015). The use of the VSM methodology is suggested in **Kühle et al. (2016)**. To provide required data, they linked VSM with QFD. With the focus on product development and quality management, QFD helps to support the development of a long-term strategy. It translates customer requirements into technically specific data. Step by step, it links these subjective customer requirements with the rational design of the product and QFD supports multi-criteria decisions (Akao and Chan 2011).

Valverde and Daniela (2019) used VSM in the forest- and wood-based supply chain to tackle the lack of information supply chain stakeholders and to improve the wood flow planning, tract allocation, truck scheduling, and communication.

The literature on the various mapping and measurement tools shows that they do not meet the necessary requirements to systematically analyze product architecture, production processes and production technologies. To tackle this lack, **Kühle et al. (2019a)** developed a multi-step Quality Function Deployment approach. In order to analyze manufacturing process chains of existing and new products, it must be clear how many product components will be designed, how each component will be produced, and how each components and manufacturing process affects and is affected by the others as well as by the technology applied. For this purpose, a conceptual framework is developed based on an adapted multi-step QFD approach with an elementary PTM. QFD uses the “House of Quality” (HOQ) which supports the transformation process. Products, services or processes are designed to meet customer demands. This is the foundation of the HoQ (Temponi et al. 1999). With a simple structure, the HoQ guides the user through the procedure to develop the QFD (Hauser and Clausing 1988; Wolfsmayr and Rauch 2014). The main function of the HOQ is a relationship matrix which assesses the impact of the product quality characteristics (PQC) on customer requirements. The main contribution of the paper is a conceptual consideration with a conceptual framework rather than providing comprehensive solutions. The approach shows that optimisation potential exists within the SH manufacturing chain based on alternative the combinations of manufacturing processes and applied technologies. Forward, results indicate that current production lines for appearance application do not support an efficient and economical production of upcoming load-bearing products.

2.2.2. Data collection about the hardwood supply chain and network

A major challenge for this work was to obtain sound specific data of the predominantly small and medium-sized enterprises. While the locations and current products are mainly known for forest departments and hardwood sawmills, other data that would form the basis for strategic network planning, such as possible production capacities or conversion yields from hardwood logs to lamella production, are hardly availabe. Also, the downstream facilities contain unknown factors. Production data and economical expense are not available or can only be assumed for the downstream facility and the customers. These data and parameters may include production capacity of the facility, production costs, the potential product demand etc.

In addition to the decomposition of the products into their product components with the help of QFD in **Kühle et al. (2019a)**, **Kühle et al. (2016)** propose to combine QFD and VSM in order to methodically build up a relevant database. After the provision of the necessary manufacturing process, the VSM enables the assignment of specific values to each process chain element in the company. This approach could not be applied in the solid wood industry to obtain more parameters about the solid wood business and its supply chains.

In many cases, the data for the necessary planning parameters was not available. In order to remedy this deficiency, various approaches to data generation were used in **Kühle et al. (2019b and 2019c)**. The data were mainly derived from existing data sources like the distribution of harvested beech wood per month from the given annual production and capacity data or were scientific guesses like the percentage of beech wood harvested per month.

2.2.3. Solid Hardwood Supply Network Design

2.2.3.1. Optimal location of laminated beech production plants within the solid hardwood supply network

In order to reengineer the hardwood supply network and to add new facilities for the downstream, new potential networks have to be designed. These alternatives can include possible suppliers, locations, production and storage capacities as well as marketing and shipment options (Klibi et al. 2010). Within the forest- and wood-based business, the opening up of new facilities are strategic decisions with long-term impact. Thus, it is also important to redesign the capacities and technologies of facilities within the divergent transformation business (Vila et al. 2006).

The collective consideration of individual production units within a hardwood supply network can help to achieve aggregated capacities and resources to satisfy a downstream demand which is impossible as a solitary company. For the solid hardwood supply network, it is necessary to think about locations of existing and new production facilities to examine if current locations are still suitable for future supply chains and where new production facilities can be integrated into existing supply networks.

Within the operational research, the SND problem restructures supply networks to achieve value creation in stakeholders involved (Klibi et al. 2010). Facility location problem (FLP) is a subset of SND or discrete problems which deal with the location of at least one facility in a given surrounding. Melo et al. (2009) identified four elementary aspects in their review which may be considered in strategic supply chain planning with FLP: I) multi-layer/multi-capacity facilities, multi commodities, single/multiple periods, as well as deterministic or stochastic parameters. For example, the benefit of using multiple periods is that SND can be adapted to parameters which change over the periods like resource availability or customer demand which is usual within the forest- and wood-based sector. Three fourth, who use the approach, apply cost minimization objectives for FLP (Melo et al. 2009).

In the forest- and wood-based sector, a high proportion of FLP publications research the utilization of woody biomass for heat and energy generation or as a resource for biorefineries. The contribution is the allocation of resource amounts and locations to plants or to biorefinery facilities as well as the opening of intermediate storage locations for the transport from source to the customer (Johnson et al. 2014; Walther et al. 2012; Kanzian et al. 2013; Gronalt and Rauch 2007; Rauch and Gronalt 2010). Advanced FLP focus on integrated facilities within a supply chain network. Integrated biorefinery and forest product SND are studied to support organizations in their investment decision (Feng et al. 2010; Abasian et al. 2017). Additionally, FLP can consider biorefineries technologies which can lead to centralized or decentralized plant concepts (Walther et al. 2012). Alayet et al. (2018) provide a forest supply network model with independent business unites which are linked through interdependent processes. The model helps to study applied supply chain management methods. In their work, they compare Make-to-Order, Vendor Managed Inventory (VMI), and a centralized planning approach. The latter leads to the highest profit. The network design is characterized by perfect collaboration. The VMI approach fits for a business environment which is more characterized by competition and non-collaborative.

Klibi et al. (2010) mentioned that there are three major classes of value drivers which should be taken into account in SND. They are revenue drivers, cost drivers and capital expenditure. All three are not necessarily relevant for SND at the same time. If models use deterministic demand for the given number of periods, the revenues can be seen as a constant and the model objective just minimizes the supply network cost.

Kühle et al. (2019b) provide a decision support model for strategic planning. The approach supports the development a supply network providing laminated beech wood products. The paper answers the important question of where the downstream facility must be located in order to obtain a supply network with the lowest costs and which hardwood sawmills should be involved in the upcoming implementation phase. It uses available specific values from the wood technology research and applies this data in the field of supply chain management. The innovation in this paper is the application of the existing models to the solid hardwood sector. The paper´s main contribution are data about the solid hardwood business and a strategic planning model for designing a supply network for laminated beech products.

2.2.3.2. Form-based postponement in the solid hardwood supply network

In contrast to **Kühle et al. (2019b)**, the approach in **Kühle et al. (2019c)** contains two markets served by sawmills: Sawn timber for furniture manufacturers and lamellas for laminated beech wood products. In order to achieve this, hardwood sawmills need flexibility in the production and order fulfillment, while keeping costs low and material yields high to deliver on time.
Using an international survey approach, Kisperska-Moron and Swierczek (2011) found that dynamic supply chains can undergo reconfigurations in response to increased demand for customized products. They concluded that a “full postponement strategy” is possible but depends on the level of product customization as well as a companies´ manufacturing and logistical capabilities.

For the forest- and wood-based sector it becomes clear that there has been a shift towards more customization and just-in-time deliveries as well as orders becoming smaller and more diverse (Espinoza et al. 2014). Mass customization concepts support these shifts and have a positive impact on the domestic market strength of the sector (Lihra et al. 2008).

Audy et al. (2012), Hauslmayer and Gronalt (2008), Gronalt and Rauch (2008) and Alayet et al. (2018) studied specific aspects of postponement in the forest- and wood-based sector. However, the literature review shows that there is potential for further postponement studies and that form postponement is not studied so far. Especially for postponement concepts in the solid hardwood supply network, there are no comprehensive case studies available. An important step in the development of the postponement concept is the identification of decoupling points along the supply chain. These points are decisions which have an influence on the downstream process and the customer's demand.
In **Kühle et al. (2019c)**, the synthesis of SND and mass customization is used to design a network with the lowest supply network cost. A form postponement concept is introduced within sawmills to enable a more flexible production. The decoupling point is relocated from the round wood procurement process to the sawmill or from the first cutting process to the second cutting process after the kiln-drying. The decision, what to produce, takes place after the drying process and with a different intermediate product, sawn wood instead of

roundwood. This shift influences the delivery time and the downstream production processes. Thus, there is a time shift of four to eight weeks to the customer depending on species and sawn board dimensions as well as a potential increase in material output.

2.3. Scenarios due to data uncertainty

Uncertainty exists in strategic planning processes with high investments. This means that at a certain point in time there is not enough information available to predict certain resources, demands, sales or other developments in the future. One method to tackle uncertainty is to develop appropriate scenarios that present and can analyse potential alternative futures perspectives (Mansoornejad 2012). Supply chain models and their uncertain data can be classified into deterministic, stochastic-probabilistic models, hybrid, IT-driven. Here, deterministic means that the value of certain variables is known. These models represent an approximation of the business reality (Chatzikontidou et al. 2017). A comprehensive review of SND under uncertainty was conducted by Govindan et al. (2017).

Within the forest- and wood-based industry, heuristics (Huka and Gronalt 2017), stochastic programming (Zanjani et al. 2013), robust optimisation (Klibi et al. 2010) and generation of scenarios (Abasian et al. 2017) are used. The latter approach is also used in **Kühle et al. (2019b and 2019c)**.

Different scenarios are presented that simulate specific assumptions to support the optimisation and evaluation of the solid hardwood SND. They deal with critical design problems. In addition, the scenario planning process aims to find a balance between taking sufficient realistic factors and maintaining the number of scenarios at a manageable level to reduce complexity.

3. Methodology

In order to meet the various challenges in solid hardwood utilisation described above, different methods have been used to combine wood technology and supply chain management.

In this thesis, multi-level QFD and PTM are used for quantitative and qualitive approaches. The optimisation approach is used to model and plan the two supply networks under consideration. In addition, process modelling is used in this thesis and finally scenarios are generated to investigate possible future configurations of the supply networks.

3.1. Multi-step Quality Function Deployment and Process Technology Matrix

This thesis is based on the methodology approach of Macabe and the American Supplier Institute (Hauser and Clausing 1988; Mai 1998). Both works use more than one "House of Quality" for a sufficient utilization. For comprehensive quality and product development management, additional HoQ are applied which consider product components (HoQ II), processes (HoQ III) and production planning (HoQ IV). The framework helps to consider and break down the complexity of the structure of the product architecture. The structure is hierarchical and consists of four phases which are divided into product, component and process planning as well as process execution. Each phase is represented in a diagram which correlates requirements with its PQC. In the following level, the previous implementations are adopted as requirements. The multi-step approach ensures systematical development (Figure 9). Adjustments were made which are explained in detail in **Kühle et al. (2019)**.

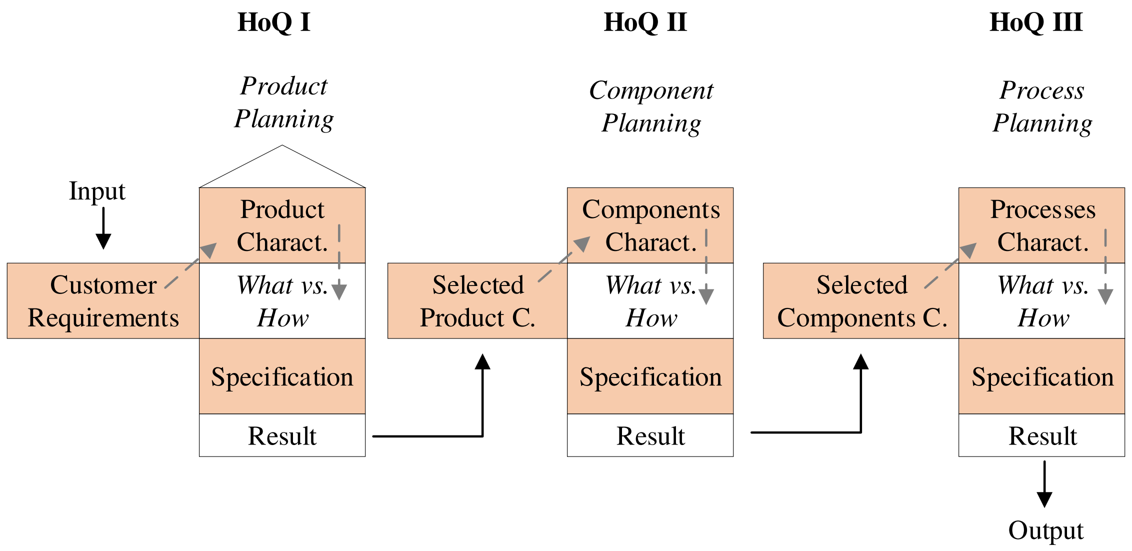


Figure 9: The three House of Qualities are combined to the multi-step approach. The predefined requirements of the HoQ I are the initialization for the development of the first HoQ. With the HoQ I relationship matrix, the user determined the influence of PQC on the pre-defined requirements. The illustrated specification section contains the PQC objectives and the evaluation part. The selected PQC of the HoQ I are included in the HoQ as input requirements for the component quality characteristics. Similar to HoQ I, HoQ II and III are executed.

The QFD standard does not take technology integration into account. Therefore, a PTM is added according to the multi-step QFD approach. It represents the firm´s ability to perform its processes with various existing technologies or modified machines. The process is taken from the direction and function of the relationship matrix of a HoQ. Instead of rating the influence of quality characteristics on the requirements, the matrix visualizes that the considered technology has an effect on the downstream process or not.

The first main step shows processes (left row), provided by HoQ III, which are necessary for a product. It also contains processes which are beyond company boundaries. In addition to the processes, the technologies are collected for each process (column). The next main step provides information about the influence of a technology on the entire process (Figure 15).

The advantage of the PTM after using QFD is that it evaluates the available technology for individual manufacturing processes, thus at the end there is a decision support to choose the appropriate technology to the necessary process which produces the required product components.

3.2. Optimisation Approach

To support the strategic design of multi-tier solid hardwood supply chain, mathematical optimisation is used in this thesis and two models are developed. Both calculate the lowest cost for the supply network. Instead of each business unit trying to optimise its own activities without considering other activities or business units in the supply network, optimisation models are developed which focus on the lowest supply network cost for the product taking into account all business unites in the network.

Kühle et al. (2019b) considers a plant location allocation within a SND and **Kühle et al. (2019c)** uses an alternative production system to improve the multi-tier solid hardwood supply network. While the first paper concerns a model with one supply chain, the second paper deals with a model with two supply chains that can be extendable to multi supply chains (Figure 10).

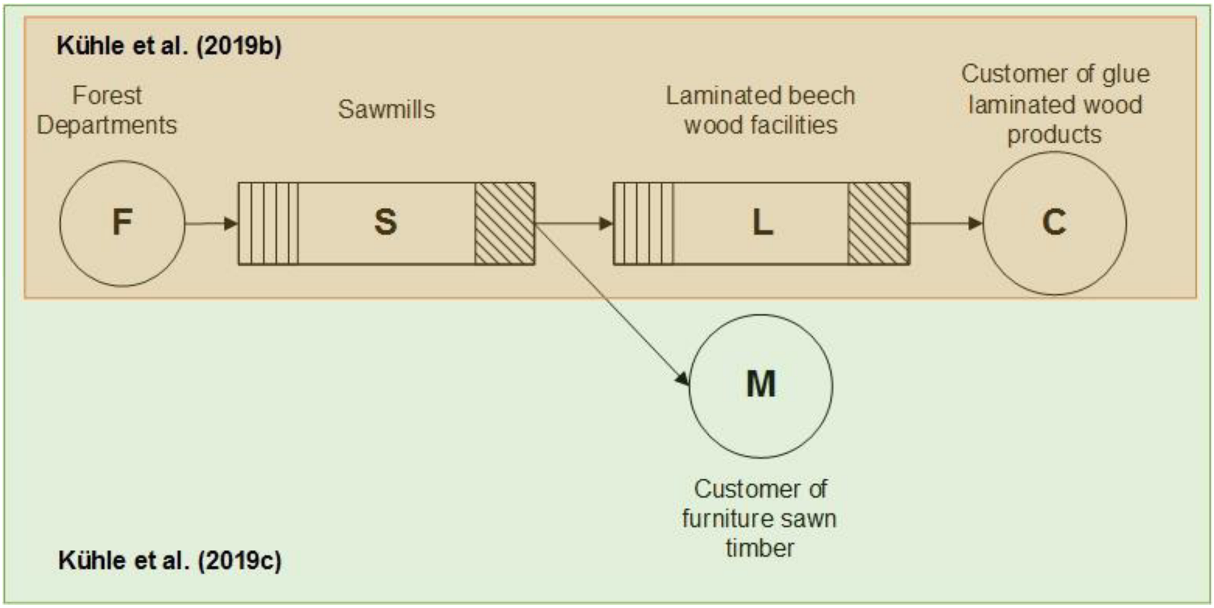


Figure 10: The models of the solid hardwood supply network considered represent the actors involved and the material flows between them. There is a direct material flow from one entity to all entities in the next tier. From the forest departments, the roundwood flows either to the customers of either laminated wood products or to the customers of the furniture sawn timber.

In **Kühle et al. (2019b)**, a mixed integer linear programming model (MILP) is proposed to find an optimal design for a general LBWSN. It contains a FLP within a multi-level supply chain. The model aims to minimize the cost of supply network by satisfying a specific product demand per year. The model considers several parameters which characterize the four entities forest departments, sawmills, laminated beech wood facility (LBWF), and customers. Decision variables are introduced to describe material flows between the entities and within the sawmills and production facilities.

It is to highlight that in the objective function the decision variable u_{tc}, unsatisfied demand of customer c in period t, is used to guarantee maximal demand satisfaction. There will be model configurations which do not satisfy the demand constraint thus a model objective value of 0 will be provided. To counteract this effect, the decision variable u_{tc} is introduced thus also a not fully achieved demand satisfaction will provide a solution. Furthermore, the model is characterized by the consideration of different production capacity options and the allocation of plants as well as the limitation of the opening up of new plants. Since there is no potential demand for the product because there is no manufacturer yet, a demand of 50,000 m^3 of laminated beech wood products per year has been assumed.

In **Kühle et al. (2019c)**, a linear programming model is purposed to find the minimal cost for the supply network which fulfils a certain demand of two product markets per year. The model considers several parameters which characterize the following five entities: forest departments, sawmills, laminated beech wood facilities, beech sawn wood for furniture market and laminated beech wood market. As in **Kühle et al. (2019b)**, the decision variables u_{cpt} and u_{mpt} were introduced to ensure the fulfilment of demand with an objective function that minimises costs. It is to highlight that time shifts have been introduced to reflect general production and delivery times. Within the sawmills, there is a time shift of *t + 2* and within the LBWF *t + 1* (4).

In addition, different material yields result from the developed process flows. They are integrated into the optimisation model with several cutting patterns to choose from. The calculations of the material yields are the basis for the subsequent numerical experiment. The additional production processes, which are responsible for a possible increase of the yield, also cause additional costs. They are presented depending on the sawmill´s production capacity and its variable production cost.

Finally, although long-term planning is addressed for both models, mid-term data is used because of the lack of it. For example, customer demand per year is used, which is split into 12 time periods.

The optimisation models for the strategic planning are calculated with the commercial optimisation software FICO Xpress-Optimizer 29.01.07.

3.3. Process Modelling

Process models are simplified images of processes of an organization. They represent the chronological-object-logical sequence of functions or activities. Depending on the objective, process models can be modeled in varying degrees of detail and scope. Due to the complexity, not all processes to be considered can usually be represented in a process model. With the help of process models, existing processes can be clearly and unambiguously documented.
In this thesis we have developed a divergent modeling of processes that are result from the PTM (Figure 11), a process flow chart for production processes in the sawmill (Figure 12) and the mathematical modeling of processes for their optimisation (Figure 13).

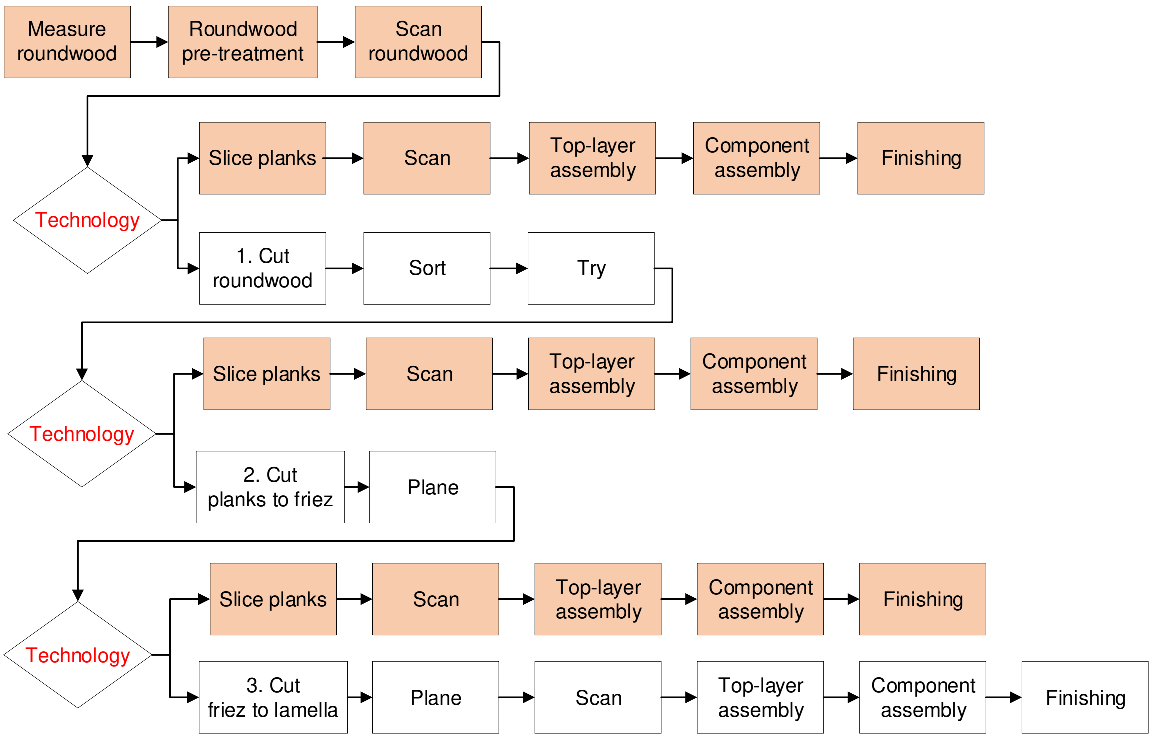


Figure 11: The divergent process chain is represented for the solid parquet production. It is a result of the general process chain development by QFD in combination with the Process-Technology Matrix. The branching took place during the technology selection. Each technology branch represents either a sawing process or a slicing process. The traditional and most commonly used approach includes the three break down processes. The new manufacturing includes one break down process which is followed by slicing **(Kühle et al. 2019a)**.

The process flow chart represents three main production process flows and connects the decisions which result in diverse material flows and different material yields. The standard process flows consist of either the production of lamellas for glued timber products as an intermediate or of the sawn timber for furniture products (#0). A third process flow is added. It represents the production of glued lamellas out of a single-layer panel. The concept is developed by Ressel (2002) and is also considered by Hönnebeck (2008).

Within the process flow chart, there are two kinds of decisions. One is a general decision of the material flow and the other is related to the quality of the input material. The general decision assumes that sawmill owners try to satisfy the demand of lamellas more than the demand of sawn timber for furniture products. 60.0% of intermediates flow into the lamella production after the kiln-drying and 40.0% into sawn timber (#1).

There are three decisions which are related to the quality of the input material and they decide if a specific input material is suitable for the next process step, which adds value to the product or not (#2, 3 and 4).

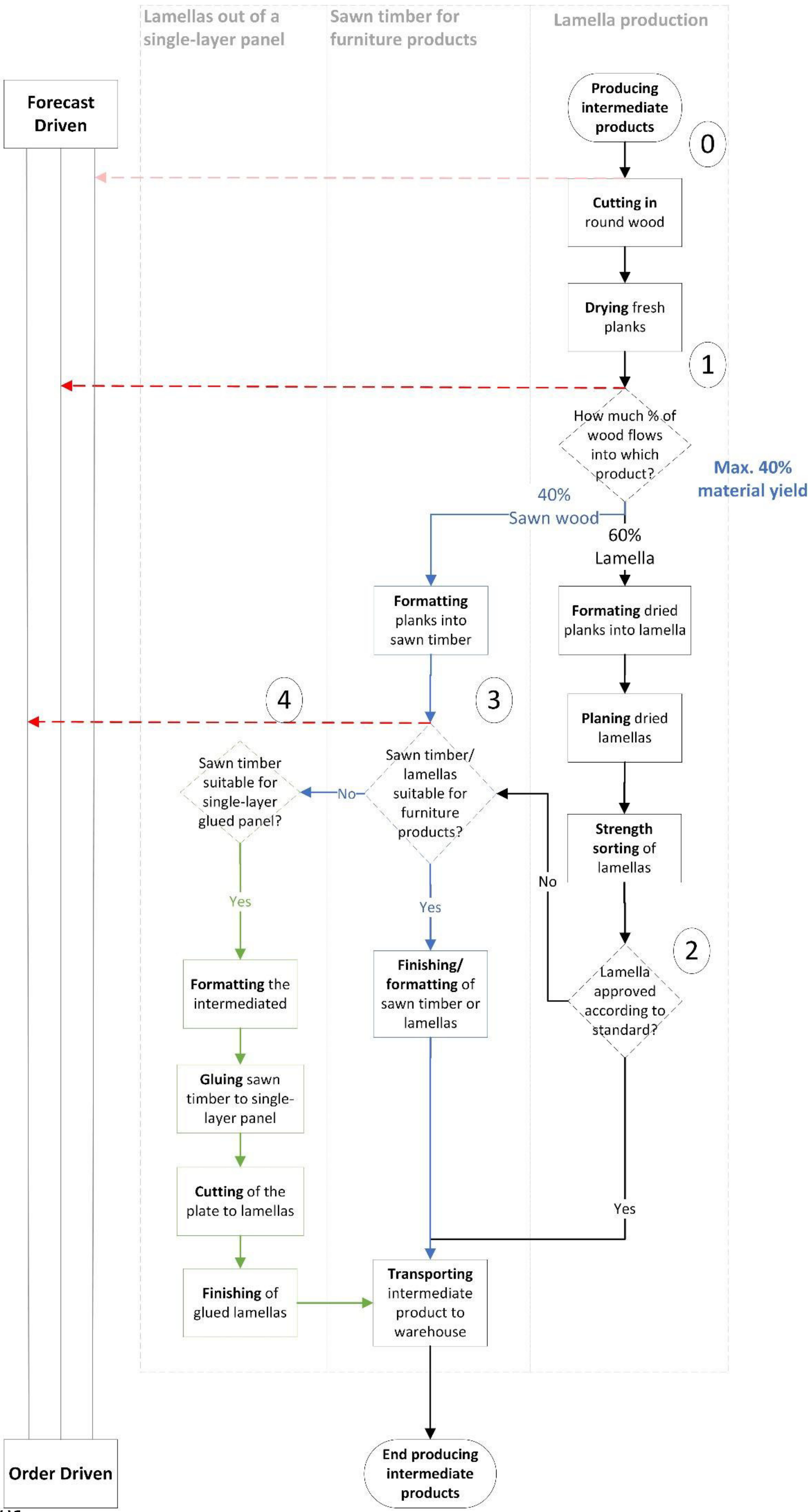

Lamellas out of a single-layer panel
Sawn timber for furniture products
Lamella production
Forecast Driven
Producing intermediate products
0
Cutting in round wood
Drying fresh planks
1
How much % of wood flows into which product?
Max. 40% material yield
40% Sawn wood
60% Lamella
Formatting planks into sawn timber
Formating dried planks into lamella
4
3
Planing dried lamellas
Sawn timber suitable for single-layer glued panel?
No
Sawn timber/ lamellas suitable for furniture products?
Strength sorting of lamellas
No
Yes
Yes
2
Formatting the intermediated
Finishing/ formatting of sawn timber or lamellas
Lamella approved according to standard?
Gluing sawn timber to single-layer panel
Cutting of the plate to lamellas
Yes
Finishing of glued lamellas
Transporting intermediate product to warehouse
Order Driven
End producing intermediate products

Figure 12: The process flow chart shows the three main production process with lamellas (right), sawn timber (middle) and single-layer panel (left). They are connected by four decisions elements which are marked with numbers. At the left, the position of the de-coupling point is presented between forecast driven and order driven. Also, the types of decisions are represented with #1 the general decision and #2, #3 and #4 the postponement decisions **(Kühle et al. 2019c)**.

In **Kühle et al. (2019b and c)** mathematical modelling is applied with MILP. Its goal is the formulation, solution and simplification of a mathematical model for a real problem from the forest- and wood-based industry. The way of mathematical modeling depends very much on the concrete problem.

In **Kühle et al. (2019b)**, a MILP is proposed to find an optimal design for a general LBWSN considering the entities forests departments, sawmills, LBWF and customers as well as a set of production capacity options and of time periods. It combines a supply network flow with a FLP. The model aims to minimize the cost of supply network by satisfying a specific product demand per year. The model considers several parameters which characterize the four entities forest departments, sawmills, LBWF, and customers. Decision variables are introduced to describe material flows between the entities and within the sawmills and production facilities

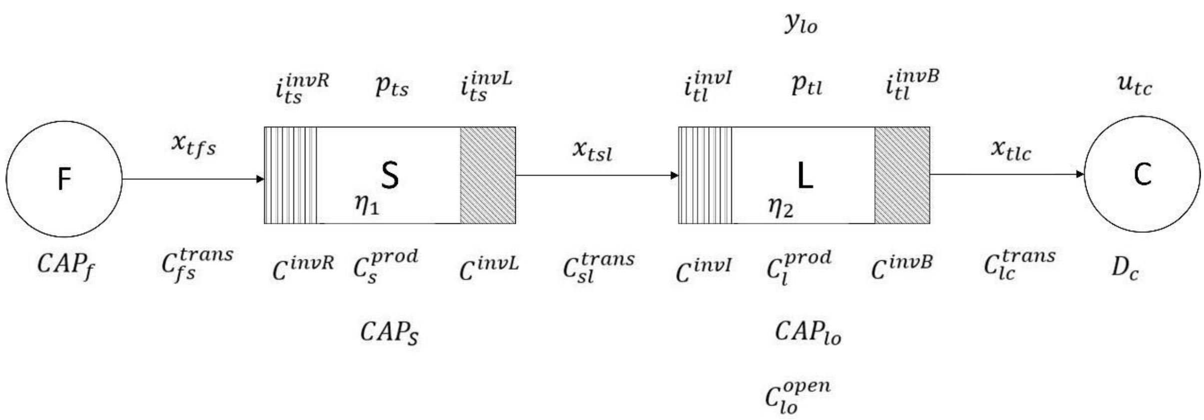


Figure 13: Generic LBWSN with the four entities forest departments (F), hardwood sawmills (S), LBWF (L) and customers (C). I, p, u, x and y represent decision variables and the notations C and D represent parameters.

Compared to the previous paper, there are additional processes in **Kühle et al. (2019c)**, since another type of processor has been added. Included are transport processes and divergent production processes (sawing policy) in the sawmill.

3.4. Scenarios Setup

In order to simulate certain assumptions, various scenarios are presented. They support the optimisation and evaluation of the solid hardwood SND. They deal with critical SND elements such as the number of sawmills and laminated beech wood facilities and amount of roundwood. In **Kühle et al. (2019b)**, the opening of a LBWF is associated with high fixed cost. Therefore, the scenarios are used to investigate whether a facility location is competitive under various configuration. A total of 14 scenarios are calculated (Table 1).

Table 1: Developed scenarios with the defined parameters **(Kühle et al. 2019b)**.

Scenarios	Additional Sawmill	Amount of facilities	Facility capacity option	Sourcing strategy	Amount of roundwood [m³]
#1		unlimited	3	AUT	146 023
#2		unlimited	3	AUT	146 023
#3		unlimited	3	AUT	146 023
#4		unlimited	6	AUT	146 023
#5	x	unlimited	3	AUT	146 023
#6	x	unlimited	6	AUT	146 023
#7	x	unlimited	3	AUT + Neighbours	358 762
#8	x	unlimited	6	AUT + Neighbours	358 762
#9	x	1	3	AUT + Neighbours	358 762
#10	x	1	6	AUT + Neighbours	358 762
#11		unlimited	3	AUT + Neighbours	358 762
#12	x	unlimited	3	AUT + Neighbours	358 762
#13	x	unlimited	6	AUT + Neighbours	358 762
#14	x	unlimited	6	AUT + Neighbours	358 762

The advantageous locations of the laminated beech wood facilities and the hardwood sawmills from **Kühle et al. (2019b)** were used for the scenario configurations of **Kühle et al. (2019c)**. Five scenarios were developed (Table 2).

Table 2: Developed scenarios with the defined parameters **(Kühle et al. 2019c)**.

Scenarios	Amount of Sawmill	Amount of facilities	Sourcing strategy	Amount of roundwood [m³]	Demand
#1	11	2	AUT	146 023	National
#2	11	2	AUT + Neighbours	358 762	National
#3	11	1	AUT + Neighbours	358 762	National
#4	11	1	AUT + Neighbours	358 762	National + Transnational
#5	11	2	AUT + Neighbours	358 762	National + Transnational

In addition to five scenarios, the three sawing policies were also used for each scenario (Table 3). The supply network configurations and saw policies, are used to calculate a total of 15 scenarios.

Table 3: Material yield and additional cost for the individual sawing policies. For each sawing policy, the material yields for lamellas (product 1) and sawn timber (product 2) are presented in %. There are relative cost expenditures for sawing policy 3 and 4 **(Kühle et al. 2019c)**.

Sawing policy	Material yield for product 1 and 2 [%]	Relative cost expenditures [%]
1 & 2	0.220 0.0; 0.215 0.179; 0.0 0.400;	0
3	0.220 0.0; 0.0 0.400; 0.215 0.230;	+10
4	0.220 0.0; 0.0 0.400; 0.297 0.230;	+35

For each modification according to the scenario configuration, an optimisation model is created and resolved.

4. Main Results and Discussion

Within the framework of the multi-tier solid hardwood supply chain, the most important results of this work are presented and discussed below. The future planning of the hardwood supply chain and its products requires cross-company information. Therefore, a method is needed that includes processes and information as well as the ability to analyse them. **Kühle et. al (2019a)** presents such a conceptual method. The developed method was designed to systematically analyze the product, process and technology and to support decisions improving hardwood operations (Figure 14 and Figure 15). It was carried out using three hardwood products as examples.

	1	2	3	4	5	6	7	8	9	10	11
11											11
10										10	
9									9	++	
8								8		+	
7							7		+		
6						6	+		-	+	+
5					5	+		-		+	+
4				4							+
3			3		++	+	-	-	+	+	+
2		2									
1	1		-		- -		-	-	+		+

HoQ I Glue-Laminated Timber — How: Product Characteristics; What: Requirements	Weighting [1-5]	Relative Share [%]		Quality Characteristics / Product Characteristics	Product Aspect	Price: Unit Cost	Material: Dimension Geometry - GL-Beam	Dimension Tolerence - length, widh, depth	Strength Class	Product Quality - Frequency of Errors (post-processing, scrap quantity)	Wood Product Humidity - final application area humidity	Surface Quality (see objective)	Production: Through-Put Time - process time	Connections of Components - quantity	Efficiency: Resource Utilisation (Input Material)	Pass Standard Requirements
Mean Value:	3,20	20,00%			#	1	2	3	4	5	6	7	8	9	10	11
Sum:	16	100,00%	Optimisation Direction			-	/	-	+	-	/	/	-	-	+	/
Kundenwünsche/ Firmenbedürfnis																
1 Higher product quality	2	12,50%				-3	3	-1	3	9	3	9	-3	0	0	9
2 Lower product cost	5	31,25%				3	1	1	3	3	0	-3	-3	3	9	0
3 Lower delivery time	4	25,00%				-1	-1	0	0	3	0	-1	9	1	3	1
4 Higher material yield (Max: Resource, Value	4	25,00%				9	3	0	0	0	0	0	0	0	9	
5 Better desing (surface)	1	6,25%				1	3	0	0	1	3	9	0	3	0	3
				Objectives		700 € / m³	Width max. 160mm | Heigth max. 600 mm	Size Accurance according to EN 390 - Width: +/- 2 mm | Hight: + 1 %/- 0,5 % | Lenght +/- 0,1 %	> 28 GL	< 1 %	according to area of application/ service classes EN 1995-1-1 (1 ~5-15 % - 2~ 10-20 %)	application area - visible or concealed (knot frequency)	40 working days	Delamination EN 14080:2013	From trunk until final main product and co-product >50%	e.g. general type approval or on case-by-case basis
				Importance abs.		42	22	3	21	46	9	8	15	22	93	25
				Importance rel.		13,7%	7,2%	1,0%	6,9%	15,0%	2,9%	2,6%	4,9%	7,2%	30,4%	8,2%

Summe
306

			System Class	Wood Body									Auxiliary Materials
HoQ II Glued-Laminated Timber			Sub-Class	Lamella									Glue
			Function	Strengh - Weigt Transfer									Connection
What Design Requirements			**How** Component Characteristics	Stem Quality	Lamella Dimension Hight	Lamella Dimension Width	Visual Strenght Grading	Machine Strength Grading	Surface Quality	Deviation	Humidity Application Area	Finger Joints	Glue Type I (EN 301)
#	**Product Characteristics**	**Objective**	**Weighting [1-5]**	**1**	2	**3**	4	**5**	6	**7**	8	**9**	10
1	Unit Cost	700 € / m³	5	3	3	1	1	1	0	0	1	3	3
2	Dimension Geometry - GL-Beam	Width max. 160mm | Heigth max. 600 mm	2	3	3	3	0	0	0	9	0	1	0
4	Strength Class	> 28 GL	3	1	3	3	9	9	3	1	1	3	0
5	Product Quality - Frequency of Errors	< 1 %	4	1	0	0	3	3	9	1	3	3	3
9	Connections of Components - quantity	Delamination EN 14080:2013	2	3	9	0	0	0	3	3	1	1	3
10	Resource Recovery (Utilisation Yield)	From trunk until final main product and co-product >50%	4	3	3	3	3	3	0	0	0	3	1
11	Pass Standard Requirements	General type approval or on case-by-case basis	1	0	3	3	1	1	3	3	1	3	3
			Objectives	EN 1316-1 | Handelsklassensortierung (HKS; trade grading) | Rahmenvereinbarung für den Rohholzhandel in Deutschland (RVR; framework agreement for wood)	12 mm > x < 30 mm	80 mm > x < 160 mm	DIN 4074-5	According to EN 385 + DIN 4074-5 (E-dyn > 13000 N/mm²)	General Type Approval Z-9.1-679 (plane max. 6 h earlier)	EN 390 - Width: +/- 2 mm | Hight: + 1 %/- 0,5 % | Lenght +/- 0,1 %	9-12 %	DIN EN 140807	Pass Delamination Assay (sufficient waiting time between application and compression)
			Importance abs.	46	63	35	57	57	54	34	23	55	40
			Importance rel.	9,9%	13,6%	7,5%	12,3%	12,3%	11,6%	7,3%	5,0%	11,9%	8,6%

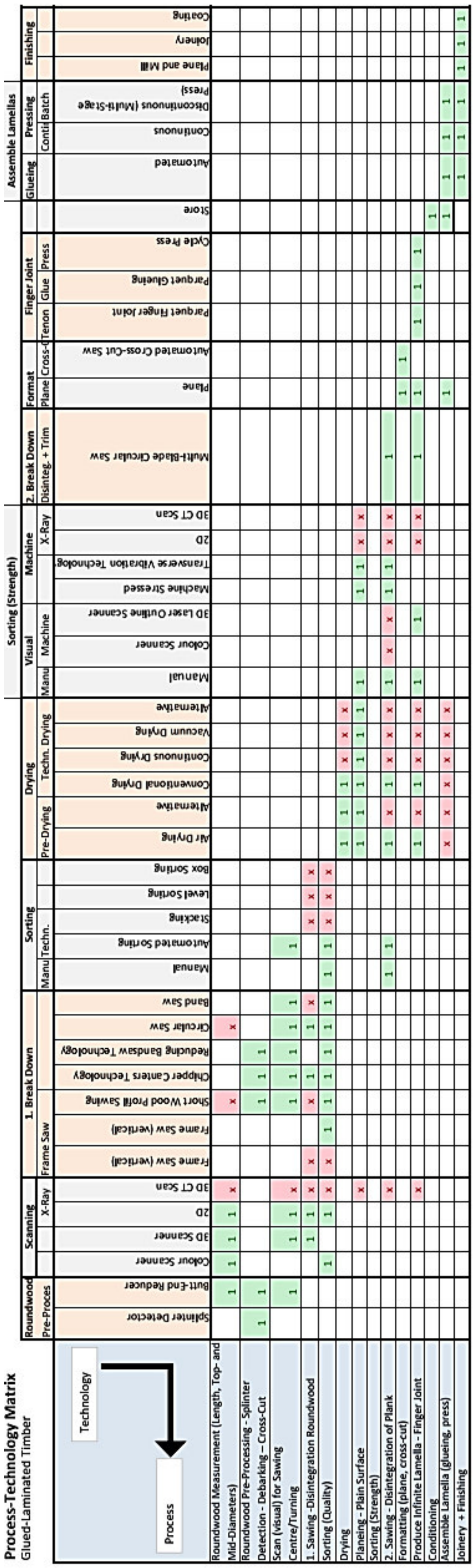
Sum **464**

			Part	Roundwood				Timber						Produce of Infinite			
HoQ III Glued-Laminated Timber **What** Component CHaracteristics From HoQ II			**How** Process	Roundwood Measurement (Length, Top- and Mid-Diameters)	Roundwood Pre-Processing - Splinter Detection - Debarking – Cross-Cut	Scan (visual) for Sawing Centre/Turning	1. Sawing -Disintegration Roundwood	Sorting (Quality)	Drying	Planeing - Plain Surface	Sorting (Strength)	2. Sawing - Disintegration of Plank	Formatting (plane, cross-cut)	Produce Infinite Lamella - Finger Joint	Conditioning	Assemble Lamella (glueing, press)	Joinery + Finishing
#	**Component Characteristics**	**Objective**	**Weighting [1-5]**	1	2	3	4	5	6	7	8	12	13	14	15	16	17
1	Stem Quality	EN 1316-1 | HKS | RVR	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2	Lamella Dimension Hight	12 mm > x < 30 mm	3	9	0	1	9	1	0	0	0	0	0	0	0	0	0
4	Visual Strenght Grading	DIN 4074-5	2	0	0	3	0	6	0	0	9	0	0	0	0	0	0
5	Machine Strength Grading	According to EN 385 + DIN 4074-5 (E-dyn > 13000 N/mm²	2	0	0	0	0	6	3	0	9	0	0	0	0	0	0
6	Surface Quality	General Type Approval Z-9.1-679 (plane max. 6 h earlier)	3	0	0	0	9	3	3	9	0	3	3	0	0	0	0
9	Finger Joints	DIN EN 140807	4	0	0	0	3	0	0	0	0	0	3	9	0	0	0
			Importance abs.	27	0	12	66	36	15	27	36	9	21	36	0	0	0
			Importance rel.	9%	0%	4%	23%	13%	5%	9%	13%	3%	7%	13%	0%	0%	0%

Sum 285

Figure 14: The three diagrams represent the results of the developed multi-level QFD and PTM approach applied to the hardwood glue-laminated timber **(Kühle et al. 2019a)**.

Process-Technology Matrix
Glued-Laminated Timber



Technology → / Process ↓	Roundwood		Scanning				1. Break Down							Sorting					Drying						Sorting (Strength) – Visual			Sorting (Strength) – Machine				2. Break Down	Format		Finger Joint				Assemble Lamellas – Glueing	Assemble Lamellas – Pressing		Finishing		
	Pre-Proces				X-Ray		Frame Saw							Manu	Techn.				Pre-Drying		Techn. Drying				Manu	Machine				X-Ray		Disinteg. + Trim	Plane	Cross-C	Tenon	Glue	Press			Conti	Batch			
	Splinter Detector	Butt-End Reducer	Colour Scanner	3D Scanner	2D	3D CT Scan	Frame Saw (vertical)	Frame Saw (vertical)	Short Wood Profil Sawing	Chipper Canters Technology	Reducing Bandsaw Technology	Circular Saw	Band Saw	Manual	Automated Sorting	Stacking	Level Sorting	Box Sorting	Air Drying	Alternative	Conventional Drying	Continuous Drying	Vacuum Drying	Alternative	Manual	Colour Scanner	3D Laser Outline Scanner	Machine Stressed	Transverse Vibration Technolog	2D	3D CT Scan	Multi-Blade Circular Saw	Plane	Automated Cross-Cut Saw	Parquet Finger Joint	Parquet Glueing	Cycle Press	Store	Automated	Continuous	Discontinuous (Multi-Stage Press)	Plane and Mill	Joinery	Coating
Roundwood Measurement (Length, Top- and Mid-Diameters)		1	1	1	1	x			x			x																																
Roundwood Pre-Processing - Splinter Detection - Debarking – Cross-Cut	1	1							1	1	1																																	
Scan (visual) for Sawing Centre/Turning		1		1	1	x			1	1	1	1	1		1																													
1. Sawing -Disintegration Roundwood				1	1	x	x		x	1		1	x			x	x	x																										
Sorting (Quality)			1		1	x	x	1	1	1	1	1	1	1	1	x	x	x																										
Drying																			1	1	1	x	x	x																				
Planeing - Plain Surface						x													1	1	1	1	1	1	1			1	1	x	x													
Sorting (Strength)																																												
2. Sawing - Disintegration of Plank						x								1	1				1	x	1	x	x	x	1	x	x	1	1	x	x	1												
Formatting (plane, cross-cut)																																	1	1										
Produce Infinite Lamella - Finger Joint						x													1	x	1	x	x	x	1		1			x	x	1	1		1	1	1							
Conditioning																																						1						
Assemble Lamella (glueing, press)																			x	x	x	x	x	x									1					1	1	1	1			
Joinery + Finishing																																							1	1	1	1	1	1

Figure 15: The PTM concentrates available information and influences which cause affects to upcoming processes. Here, the PTM is shown for the hardwood glue-laminated timber **(Kühle et al. 2019a)**.

In order to comply with standardisation and national approvals, future hardwood products should focus more on the technical data of components and process parameter to ensure the quality of the assembled product. Hardwoods have specific properties which can be addressed by appropriate technology concepts to target them in different applications. For appearance applications and new construction products, several product components should performance optimally in terms of dimension, wood moisture content or gluing system. The section objectives of the HoQ defines target values and quality objectives which support the compliance of the required parameters.

According to (Marsillac and Roh 2014), "product architecture changes that are more substantial and complex will generate more substantial and complex changes in the process and supply chain systems associated with them". This can be illustrated for the three hardwood products and their subordinated application classes. In contrast to the solid panel and parquet product, the hardwood GLT product differed in the application area, number of manufacturing processes and the types of processes which are shown in HoQ III and the PTM. In addition, the applied GLT technology and its degree of complexity were differed (Tani and Cimatti 2008).

Marsillac and Roh (2014) also note that production lines are designed to meet manufacturing needs with their specific design characteristics. For the solid hardwood industry and the selected products in **Kühle et al. (2019a)**, this means that it will be difficult to achieve economical production for high technical products for construction applications if the sawmill´s production lines were designed to meet requirements for appearance applications. For example, existing saw patterns that are tailored to the requirements of sawn timber for optical products must be rebuilt or adapted to building products so that the product process portfolio fits along the supply chain and individual companies (Abasian et al. 2017, Torno et al. 2013).

For the practical implementation of **Kühle et al. (2019a)**, the utilization of the multi-step procedure was not that challenging as collecting of production process information and data. Considering the manufacturing of hardwood GLT, there was an information gap in how to produce hardwood lamellas economically, from roundwood down to the beam and which technology should be applied along the supply chain.

Results imply that upcoming manufacturing systems must match the specific product design requirements in the solid hardwood supply chain. These requirements change for easy or complex innovative product as well as for products which have been determined for different application areas – here for appearance or construction applications. Also, it turns out that potentials are present in the production of solid hardwood products, they are based here on a change of the production processes in the context of intermediate products and technology. In **Kühle et al. (2019c)** one possibility is discussed further.

In addition to the paper already presented, there is a paper which represents an approach for the inclusion of production parameters in order to take these into account for further planning approaches. In contrast to the analysis tool of **Kühle et al. (2019a)**, this paper supports to provide characteristic values from the manufacturing processes by using Value Stream Mapping in the final step of the mulit-step QFD approach. The VSM method was not considered feasible by companies to apply it to wood products, although new research shows a different perspective (Valverde and Daniela 2019).

Kühle et al. (2019b) investigate the expansion of a future LBWSN, which is a combination of already existing and new production facilities. For a better future use of hardwood raw materials it is necessary to consider the whole supply chain.

The results are presented for the cost parameters which are given in €/m³ for the satisfied individual demand per scenario and for the material parameters in % per scenario. Also, the degree of production capacity utilization for sawmills is shown with a bar chart and the opened LBWF (Figure 16).

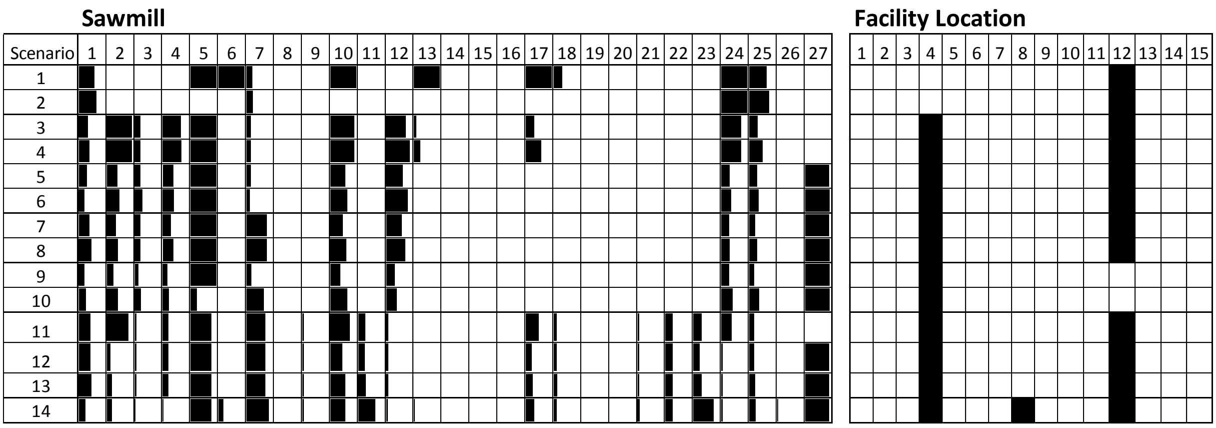


Figure 16: For all 14 scenarios, the used sawmills and facilities are represented. For the facility locations, it is just shown if it is opened. The degree of sawmill capacity utilization is shown with percentage bar sizes. The additional sawmill 27 is used every time when it was possible **(Kühle et al. 2019b)**.

For the single-product solid hardwood supply network, the used sawmill can be classified in three groups: sawmills which I) manufacture beech and have a production capacity equal or higher 20 000 m³ of roundwood, II) manufacture beech and have a production capacity lower 20 000 m³ of roundwood or III) manufacture no beech and have a production capacity lower 20 000 m³ of roundwood. The last two groups of sawmills require an increase in production capacity such as new or improves technology. This may benefit the owner and the whole LBWSN, but it calls into question the hardwood network, which consists of stakeholders with own objectives.

Another sawmill has been integrated to understand the impact that different entities and parameters can have on the supply network (Figure 16, sawmill 27). Besides the full use of its capacity, the opening of the sawmill can reduce the network production and transport costs 5 €/m³ each. The results for the opened facility locations are robust. The same two locations are selected on a recurring basis for the 14 scenarios with different network configurations in order to meet demand cost-effectively. Here is to highlight that both opened facilities have bigger suppliers of lamellas in their closer distance which result in lower transport and production cost.

The possibility to store raw materials and products has an impact to satisfy the demand. Inventory plays an important role in considered supply network model because roundwood and products are stored to provide them when they are needed. The availability of roundwood is decreasing from spring time and whereas the demand from the side of the sawmills starts to raise. Products and raw material are used from the storage to satisfy demand. After May or June, the supply curve goes down because roundwood is not economically available anymore although demand of final products and roundwood are still existing **(Kühle et al. 2019b)**. It is to point out that the model has no storage limit constraints, but they could be added easily.

By design, the optimisation model focusses on strategic planning to choose the optimal LBWF locations and material flow within the production network. For the model, the period of scope is one year with 12 periods. It does not consider future resource increment of the local forest sources. For investors, the investment horizon is an important aspect which can be 15 years and more. Studies show that there is an increase in hardwood stocks and that the trend goes on (Berendt et al. 2017). This has an impact on the overall supply network cost. To anticipate the consequences for this cost, the results from the national and the transnational sourcing strategy are compared **(Kühle et al 2019b)**. It can be assumed that the production cost will decrease per m³, the opening cost stays stable and the satisfied demand will increase. Transportation cost increase because of the longer roundwood allocation distances and in order to supply more customers. It is to be highlighted that this can increases the degree of demand fulfillment by 18%. In total the overall cost of transport increases. It can be assumed that saw log transport cost will decrease with a higher amount of local resources available.

In **Kühle et al. (2019b and 2019c)**, the demand of 50 000 m³ glued laminated beech wood products was determined. Just like the quantity of resources, the demand side cannot be predicted with certainty. Should demand be higher than expected, this would have a major impact on the network structure. In the case laminated wood product demand increases from

3% to 10%, for example, this can result in economies of scale affecting the total cost of supply chain as described in Song and Sun (2016).

Italy and Germany are the main buyers of Austrian wood-products. Therefore, 60% of the demand are located transnational. If the additional demand is considered in the calculations, the result is a slightly different network design and material flow. The satisfied demand reaches 76%, which is 1% more than for the national demand only.

Data visualized like in Figure 16 can help to decide which stakeholders should be cooperating to ensure reduced network and product costs. Results are available on consumed and transported quantities as well as used forest departments, sawmills, opened facilities and customer locations leading to optimised material flows through the supply network. An important finding is that the production of laminated beech wood products must be a cooperative planning between existing stakeholder and new ones. Instead of individual stakeholder goals, we have defined an overall supply network objective. The potential LBWSN can lead to sawmills with high qualitative manufacturing and reliable supply of beech lamellas and to LBWF, which focuse on the production of high-quality laminated beech wood products and the satisfaction of end customers.

Kühle et al (2019b) considers the minimal supply network cost from raw material to the customer and integrated transport as well specific manufacturing activities of the production units. Beyond the paper of Torno et al. (2013), this paper integrated the decision to open LBWF at determined locations as well as transportation activities between the units and before and after the hardwood sawmills. Furthermore, it considered location positions of the production units as well as capacity differentiations of the sawmills and the LBWF.

Ouhimmou et al. (2008) conducted an analyze of a specific furniture company by using their internal dataset and compared computed results with the results of the company planning process. The provided dataset helped the authors to find potential performance improvements. The main reason for the improvements increase was matching sawing policies and hardwood logs to the customer´s demand configuration. In **Kühle et al. (2019b)**, only one material yield is used for the sawing process for one class of beech logs which was provided by Torno et al. (2013). At this point, there is potential for further studies which should consider different sawing policies for various log dimensions or alternative sawing policies which go along with the new intermediate products (see **Kühle et al. 2019c**). Also, if there is a deeper study of the LBWSN, it will be necessary to conduct a broader study for collaboration between the beech wood production units either through information or resource sharing. D´Amours and Rönnqvist (2008) report that this results in decreased cost of executing the logistics activities, improve service, gain market shares, enhance capacities as well as protect environment and mitigate climate change Issues. Just as authors before, Abasian et al. (2017) reported that collaboration has a significant effect on the supply network profit.

As well as Feng et al. (2010) emphasize it, the used optimisation model is also capable in evaluating various network designs with depended production unit parameters and amounts to find the minimal cost of the supply network, but the results are scenario sensitive. Therefore, further particular business data is required as well as scenario studies.

Findings for form-based postponement for the forest- and wood-based sector especially on hardwood

In **Kühle et al. (2019c)**, the form postponement involves the delay of activities that determine the form and function of products. This makes it necessary to adapt product processes or product components such as dimensions. This is also true for this research work, as Figure 12 shows where these adjustments and changes occur. Similar to van Kampen (2013), the implementation of form postponement is only within a single location. The literature shows that if several production units were needed to implement the postponement concept, then the process costs for all involved would increase and the knowledge about quality and quality fulfilment would decrease, since several production sites are involved and a higher exchange of information is needed. Form postponement within a single production unit is possible due to the modularity of the products, material and dimensions. The literature refers to product and process modularity as an enabler for form postponement (Forza et al. 2008). This change in the production chain has an impact on the downstream like on the material yield or on the entire supply network cost (**Kühle et al. 2019c**).

A common advantage of postponement is seen in the reduction of uncertainty in the literature (Hoek 2001). This statement cannot be answered directly in **Kühle et al. (2019c)**. From the results and the process flow chart can be said that on the one hand the combined processes lead to a higher material yield and on the other hand the specification of the product can be carried out later in production. This is possible by the modularity of the products, by finishing processes at the end of the production chain in the sawmill and by the possibility to make decisions to produce certain products in the production by increased decoupling point. For the supply network and the fulfilment of customer requirements, this could lead to greater flexibility and possibly to shorter delivery times.

The results of the SP 4 scenario show that new cutting patterns have to be developed in order to fit the product process portfolio along the supply chain and for individual companies (Abasian et al. 2017). The individual total cost comparison of SP4 to the variants of SP 2 and 3 shows that cost reductions are possible there (table 4). The result suggests that it is more likely to buy raw materials nationally and satisfy customer demands, as S1's cost reductions are the highest in comparison to the other scenarios. Here it must be pointed out that the scenario serves the lowest demand of the absolute quantity. Delivery transport costs have an important role to play here. It must be taken into account that with an increased demand, the distances to the individual customers also increase and thus the transport costs also rise proportionately. This is especially true when roundwood is procured abroad and derived from distant locations. The same applies to end products. This effect can also be seen in **Kühle et al. (2019b)**. They give literature recommendations, which deal more specifically with this challenge and with further challenges in the hardwood production network.

Table 4: Here the relative reduced costs per m³ compared to the SP values are alongside the relative additional costs**.** Negative *rel ∆ total cost* must be compared to positive *rel sup cost*.

Comparison of sawing policies	$rel\,\Delta\,total\,cost$ [%] S1	S2	S3	S4	S5	$rel\,sup\,cost$ [%] Min	Max
3 & 2	-0.6	0.6	1.3	2.0	2.5	1.0	1.5
4 & 2	-4.6	-2.6	-0.2	0.8	0.2	3.4	5.4
4 & 3	-4.0	-3.2	-1.5	-1.2	-2.3	3.4	5.4

For strategic planning of the supply network, the form postponement developed here and the associated adjustments to the production processes have the advantage that they lead to increased material utilization. On the supply side, this leads to lower demand for raw materials within the supply network and to an increased satisfaction of demand on the customer side. This is reflected in the increases in capacity utilisation in processing and the constant capacity in the sawmill (table 5). Both could lead to clear financial advantages, which would have to be considered in tactical planning and operational execution. There is still potential for further work to move from strategic planning to a daily implementation.

Within the solid hardwood production network, sawmills face the greatest challenges. The production processes that lead to a diverse material flow also results in the most changes. However, this work shows that there are several decision-making options leading to further room for action. In addition to retaining the existing products, it is possible to switch completely to new products, to stay with the known products or to use a mixed form. For the latter, this work shows that with the help of the developed production processes, further points in the process flow arise at which the production of an intermediate can be decided. This gives the producer more flexibility in meeting demand.

When it comes to the question of resource strategy, this model reaches its limits because the scenario with the shortest path also generates the lowest costs. Here it is the national resources supply and national product demand. Although hardwood is a locally available commodity, it is traded globally. In Central Europe, for example, Beech can be sourced relatively well locally and nationally, but most producers supply a transnational or global demand (Luppold and S. Bumgardner 2015).

5. Conclusion and Further Research Paths

This thesis proposes a new approach for mulit-tier solid hardwood supply chains. Solutions are based on qualitive methodologies such as Quality Function Deployment and Process Technology Matrix to analyse supply chains cross-company, optimisation techniques for the strategic planning of the SND and postponement strategy from the field of mass customization to overcome challenges within the supply network.

With regard to the methods developed, it should be noted that they can be applied in many ways to other forest- and wood-based products and supply chains. Although the optimisation models were mainly applied to laminated hardwood products, the models can be easily adapted. Either there are specific changes to the model or by the input data used.

Kühle et al. (2019a) includes a conceptual framework for a methodology to disaggregate solid hardwood products. The approach has examined the possibility of integrating product architecture, manufacturing processes and technology solutions into a systematic approach in order to analyze and identify the relations between them and how the relations have affected each other. The solid hardwood products panel, parquet and GLT have been chosen to illustrate the concept. Based on multi-step QFD and PTM approach, requirements on products have been represented by the HoQ I. The match of product components and manufacturing processes has been devised with the HoQ II and III. The potential influence of a chosen technology has been demonstrated with the PTM. Manufacturing systems must match the specific product design requirements. These requirements change for easy or complex innovative product as well as for products which have been determined for different application areas – here for appearance or construction applications.

Kühle et al. (2016) is a supplement to the first. It shows that qualitative data can be collected as well as quantitative on production processes within the multi-tier hardwood supply chain. Value Stream Mapping is recommended for this purpose.

Kühle et al. (2019b) provides data for the solid hardwood business and develops a MILP model for the design of an LBWSN. For a new hardwood product, the model covers the important strategic decision where to locate a glued laminated wood facility within the existing production network with the lowest supply network cost. The results of the optimisation model, e.g. material flows and sawmills involved, can be considered for further planning. From the allocation of a production site, the continuous laminated beech wood production must be guaranteed by a secure lamella supply by the sawmills. It will be challenging to develop a cooperation planning of the network actors on a tactical and operational level.

In **Kühle et al. (2019c)**, an optimisation model is proposed to analyse the impact of a new, innovative product within the existing solid hardwood supply chain. In addition, a postponement strategy was developed and defined in order to add flexibility to the supply of solid hardwood products for two different markets. For this end, alternative production processes were developed and presented, which also led in new material yields. The approach presented in the paper shows that sufficient raw materials are available to serve the market of sawn beech timber for furniture according to the defined demands. In the case of laminated beech wood products, it is not the raw material or the capacities of the sawmills that are a limitation, but the capacities of the downstream production. There is unused capacity, both on the resource side and on the manufacturing side. The challenge of individual resource locations or sawmills arises when the decentralized production concepts of the stakeholders are considered in detail. The consideration and integration of alternative production processes have led to lower supply network costs and increased utilisation of raw materials.

The advantage of form postponement concepts lie in shorter delivery times, which however come with higher production costs (Waller et al. 2000). When deciding on the it, companies face an increase in production costs and an increase in expected revenues due to a better estimate of demand. Therefore, it is important for companies to find the optimal balance between costs and benefits achieved by the postponement process (Bagchi and Gaur 2018).

Finally, the challenges that arise during the conversion of production processes and the application of the form postponement concept, can be mastered at an early stage by through change management. This change management is mentioned as the single most critical success factor during such major adaptions of processes (Hoek 2001). For the hardwood supply network, factors which support this change process are, for example, more administration and planning skills to adapt to fast changing production requirements, powerful, flexible, as well as user-friendly Information technology and the increase of labour skills such as the degree of technical competence and flexibility (Lihra et al. 2008).

Future Research

The conceptual frameworks and strategic planning must followed by further leading to tactical planning and operational implementation. For example, facility layout planning is a process that requires continuous improvement to adapt to new products, market changes and alternative production technologies. Also, the seasonal nature of raw material supply has a major influence on the storage assignment and internal logistics. Here, concepts such as multi-period or rolling horizon planning could be used to tackle challenges on the tactical level.

With future supply chains such as laminated beech products, a clear supply chain management must be established in the future due to the potential demand quantity. Although the volume of 50 000 m³ of laminated wood products in the forest- and wood-based sector is minimal, this is not the case for the solid hardwood sector. To achieve this, several log suppliers and hardwood sawmills must efficiently exchange material and information with each other in order to save costs and time. Papers, which already tackled aforementioned aspects, show that a comprehensively developed model with well detailed data can identify further potentials in unused capacities. Thus, simultaneous considerations of the mechanical, production and network aspects will lead to further cost reductions within the LBWSN (Ouhimmou et al. 2008; Audy et al. 2012).

Overall, the biggest challenge is to provide data for the model parameters in order to create additional planning models to support decision making for participants in the hardwood supply chain.

6. Publication Bibliography

Abasian, F.; Rönnqvist, M.; Ouhimmou, M. (2017): Forest Fibre Network Design with Multiple Assortments: a case study in Newfoundland. In *Canadian Journal of Forest Research* 47. DOI: 10.1139/cjfr-2016-0504.

Aicher, S. and Ohnesorge, D. (2011): Shear strength of glued laminated timber made from European beech timber. *European Journal of Wood and Wood Products*. Vol. 69 No. 1. pp. 143–154.

Akao, Y.; Chan, C. (2011): Historical development and the basis of QFD. ISQFD 2011 - 17th International QFD Symposium. 2011.

Alayet, C.; Lehoux, N.; LeBel, L. (2018): Logistics approaches assessment to better coordinate a forest products supply chain. In *Journal of Forest Economics* 30, pp. 13–24. DOI: 10.1016/j.jfe.2017.11.001.

Audy, J.-F.; Moreira, M.; Westlund, K.; D'Amours, S.; LeBel, L.; Rönnqvist, M. (2012): Alternative Logistics Concepts Fitting Different Wood Supply Situations and Markets. In *CIRRELT research report*.

Bagchi, S. S.; Gaur, J. (2018): Optimization of postponement process for a two stage modular manufacturer. In *Journal of Global Operations and Strategic Sourcing* 11 (1), pp. 39–54. DOI: 10.1108/JGOSS-03-2017-0009.

Berendt, F.; Fortin, M.; Jaeger, D.; Schweier, J. (2017): How Climate Change Will Affect Forest Composition and Forest Operations in Baden-Württemberg—A GIS-Based Case Study Approach. In *Forests* 8 (8), p. 298. DOI: 10.3390/f8080298.

Bigliardi, B.; Bottani, E. (2010): Performance measurement in the food supply chain: a balanced scorecard approach. In *Facilities* 28 (5/6), pp. 249–260. DOI: 10.1108/02632771011031493.

Bollmus, S.; Gellerich, A.; Schlotzhauer, P.; Behr, G.; Militz, H. (2017): Hardwood research at the Georg-August University of Goettingen. In *6th International Scientific Conference on Hardwood Processing*.

Brus, D.J.; Hengeveld, G.M.; Walvoort, D.J.J.; Goedhart, P.W. ; Heidema, A.H.; Nabuurs, G.J.; Gunia, K. (2011): Statistical mapping of tree species over Europe. European Journal of Forest Research 131 (1): 145–157.

Chatzikontidou, A.; Longinidis, P.; Tsiakis, P.; Georgiadis, M. (2017): Flexible supply chain network design under uncertainty. Chemical Engineering Research and Design. 128. 10.1016/j.cherd.2017.10.013.

D’Amours, S.; Rönnqvist, M. (2010): Issues in Collaborative Logistics. 10.1007/978-3-642-12067-1_22.

Dos Santos, J. G.; Santa-Eulalia, L. A. De; Silva, A. L. Da (2015): Dynamic-Value Stream Mapping (d-Vsm): A Proof-of-Concept Case. In : 22nd EurOMA - Operational Management for Sustainable Competitiveness, June 26 - July 1, 2015. Neuchâtel, Switzerland (22nd EurOMA - Operational Management for Sustainable Competitiveness).

Ehrhart, T., Fink, G., Steiger, R. and Frangi, A. (2016): Strength grading of European beech timber for the production of GLT & CLT. *Meeting 49 of the International Network on Timber Engineering Research.* pp. 29–42.

Espinoza, O.; Buehlmann, U. (2018): Cross-Laminated Timber in the USA. Opportunity for Hardwoods? In *Curr Forestry Rep* 4 (1), pp. 1–12. DOI: 10.1007/s40725-018-0071-x.

Espinoza, O.; Buehlmann, U.; Bumgardner, M.; Smith, R. (2014): Intermediaries in the U.S. Hardwood Lumber Market: Comparing and Contrasting Sawmills and Distributors. In *BioResources* 9. DOI: 10.15376/biores.9.4.6527-6539.

FAOSTAT (2017): Domain Code: FO (Forestry Production and Trade); Area Code: 11,79,97,98,167,198,199; Element Code: 5516 (Production); Item Code: 1604 (Sawlogs and veneer logs, non-coniferous); Year: 2015; Unit: m^3. [Cited 22.05.2017].

Feng, Y.; D’Amours, S.; LeBel, L.; Nourelfath, M. (2010): Integrated Bio-Refinery and Forest Products Supply Chain Newtork Design Using Mathematical Programming Approach. In *CIRRELT. DOI:* 10.13140/RG.2.1.1979.2081.

Fleischmann, B.; Meyr, H.; Wagner, M. (2002): Advanced planning. In: Stadtler, H., Kilger, C., Supply chain management and advanced planning—Concepts, models, software and case studies, Springer, Berlin, pp. 71–96.

Govindan, K.; Fattahi, M.; Keyvanshokooh, E. (2017): Supply chain network design under uncertainty: A comprehensive review and future research directions. European Journal of Operational Research. Vol. 263. Issue 1, pp. 108-141. DOI: 10.1016/j.ejor.2017.04.009.

Grabner, M., Wolf, A., Schwabl, E. and Schickhofer, G. (2016): Methods of forming veneer structures. *WCTE 2016. 16th International Conference on Timber Engineering.* pp. 849–858.

Gronalt, Manfred; Rauch, Peter (2007): Designing a regional forest fuel supply network. In *Biomass and Bioenergy* 31 (6), pp. 393–402. DOI: 10.1016/j.biombioe.2007.01.007.

Gronalt, M.; Rauch, P. (2008): Vendor managed inventory in wood processing industries - A case study. In *Silva Fennica* 42, pp. 101–114. DOI: 10.14214/sf.267.

Grosser, D. (2011): Die Hölzer Mitteleuropas: Ein mikrophotographischer Lehratlas [The woods of Central Europe: A microphotographic teaching atlas]. Springer. ISBN: 3642665772. (In German).

Hauser, J. R.; Clausing, D. (1988): The House of Quality. In *Harvard Business Review*.

Hauslmayer, H.; Gronalt, M. (2008): Mass customisation in the woodworking industry – a simulation study for the parquet flooring industry. In *International Journal of Mass Customisation* 2. DOI: 10.1504/IJMASSC.2008.017139.

Hayes, R.; Wheelwright, S. (1979): Link Manufacturing Process and Product Life Cycles. In *Harvard Business Review*.

Hoek, R. (2001): The rediscovery of postponement a literature review and directions for research. In *Journal of Operations Management* 19, pp. 161–184. DOI: 10.1016/S0272-6963(00)00057-7.

Hübner, U. (2014): Mechanische Kenngrößen von Buchen-, Eschen- und Robinienholz für lastabtragende Bauteile. [Mechanical characteristics of beech, ash and robinia wood for load-bearing components]. *Monographic Series TU Graz*. Vol. 3. Verlag d. Technischen Universität Graz. Graz. (In German).

Huka, M. A.; Gronalt, M. (2017): Model development and comparison of different heuristics for production planning in large volume softwood sawmills. Engineering Optimization, 49(11):1829–1847.

Iacocca, K.; Liberatore, M. (2018): An empirical study of service postponement. Locating the push–pull boundary. In *International Journal of Production Research* 56 (12), pp. 4100–4114. DOI: 10.1080/00207543.2018.1436786.

Johnson, D. M.; Jenkins, T. L.; Zhang, F. (2014): Methods for optimally locating a forest biomass-to-biofuel facility. In *Biofuels* 3 (4), pp. 489–503. DOI: 10.4155/bfs.12.34.

Kanzian, C.; Kühmaier, M.; Zazgornik, J.; Stampfer, K. (2013): Design of forest energy supply networks using multi-objective optimization. In *Biomass and Bioenergy* 58, pp. 294–302. DOI: 10.1016/j.biombioe.2013.10.009.

Kaplan, R. S.; Norton, D. P. (2007): Using the Balanced Scorecard as a Strategic Management System. In *Harvard Business Review*, 2007 (85(7)).

Kisperska-Moron, D.; Swierczek, A. (2011): The Selected Determinants of Manufacturing Postponement Within Supply Chain Context: An International Study. In *International Journal of Production Economics* 133, pp. 192–200. DOI: 10.1016/j.ijpe.2010.09.018.

Klibi, W.; Martel, A.; Guitouni, A. (2010): The design of robust value-creating supply chain networks. A critical review. In *European Journal of Operational Research* 203 (2), pp. 283–293. DOI: 10.1016/j.ejor.2009.06.011.

Krackler, V.; Keunecker, D.; Niemz P.; Hurst, A. (2011): Possible Field of Hardwood Application. In *WOOD RESEARCH* (56 (1)), pp. 125–136.

Krackler, V.; Keunecke, D.; Niemz, P. (2010): Verarbeitung und Verwendungsmöglichkeiten von Laubholz und Laubholzresten. Zusammenstellung aus den Abschlussberichten Verarbeitung und Verwendungsmöglichkeiten von Laubholz und Untersuchungen zur Verwertung von bei Laubholz anfallenden Holzresten. [Processing and use of hardwood and hardwood residues. Compilation of the final reports on the processing and possible uses of hardwoods and investigations into the utilisation of residual wood from hardwoods]. Zürich. (In German).

Kühle, S.; Teischinger, A.; Gronalt, M. (2016): Structure analysis of a production network by means of quality function development and values stream mapping. In J. Eberhardsteiner, W. Winter, A. Fadai, M. Pöll (Eds.): Proceedings of the World Conference on Timber Engineering (WCTE 2016). With assistance of J. Eberhardsteiner, W. Winter, A. Fadai, M. Pöll. World Conference on Timber Engineering (WCTE 2016). Vienna, Austria, August 22-25, 2016. Vienna University of Technology, Austria.

Kühle, S; Teischinger, A; Gronalt, M (2019a): Connecting Product Design, Process, and Technology Decisions to Strengthen the Solid Hardwood Business with a Multi-Step Quality Function Deployment Approach. Bioresources 14(1): 2229-2255. DOI: 10.15376/biores.14.1.2229-2255.

Kühle, S; Teischinger, A; Gronalt, M (2019b): Optimal location of laminated beech production plants within the solid hardwood supply network in Austria. Silva Fennica vol. 53 no. 3 article id10074. 22 p. DOI: 10.14214/sf.10074.

Kühle, S; Teischinger, A; Gronalt, M (2019c): Form-based postponement in the solid hardwood supply network. Cogent Business & Management. DOI: 10.1080/23311975.2019.1701887.

Lihra, T.; Buehlmann, U.; Beauregard, R. (2008): Mass customisation of wood furniture as a competitive strategy. In *IJMASSC* 2 (3/4), p. 200. DOI: 10.1504/IJMASSC.2008.017140.

Lin, C.; Chang, C.-C. (2015): The effect of technological diversification on organizational performance: An empirical study of S&P 500 manufacturing firms. Technological Forecasting and Social Change. Volume 90. Part B. 575-586. DOI: 10.1016/j.techfore.2014.02.014.

Luppold, W.; Baumgardner, M. (2015): Examination of worldwide hardwood lumber production, trade and apparent consumption: 1995-2013. In *Wood and Fiber Science* (47(3)), pp. 283–294.

Luppold, W.; Bumgardner, M. (2004): An examination of eastern U.S. hardwood roundwood markets. In *Forest Products Journal* (54(12)), pp. 203–208.

Luppold, W.; Bumgardner, M. (2015): Examination of worldwide hardwood lumber production, trade, and apparent consumption: 1995-2013. In *Wood and fiber science: journal of the Society of Wood Science and Technology* 47, pp. 283–294.

Mai, C. (1998): Effiziente Produktplanung mit Quality Funktion Deployment. English: Efficient product planning with Quality Function Deployment. Springer-Verlag.

Mansoornejad, B. (2012): Desgin for flexibility in the forest biorefinery supply chain. Dissertation. École Polytechnique de Montréal, Montréal, Canada. Départment de Genie Chimique.

Marsillac, E.; Roh, J. J.(2014): Connecting product design, process and supply chain decisions to strengthen global supply chain capabilities. In *International Journal of Production Economics* 147, pp. 317–329. DOI: 10.1016/j.ijpe.2013.04.011.

Melo, M. T.; Nickel, S.; Saldanha-da-Gama, F. (2009): Facility location and supply chain management – A review. In *European Journal of Operational Research* 196 (2), pp. 401–412. DOI: 10.1016/j.ejor.2008.05.007.

Ministerial Conference on the Protection of Forests in Europe (2015): Forest Europe, 2015. State of Europe's Forests 2015. Madrid: Ministerial Conference on the Protection of Forests in Europe.

Niemz, P.; Sonderegger, W. U. (2017): Holzphysik. Physik des Holzes und der Holzwerkstoffe [Wood physics. Physics of wood and wood-based materials]. Hansa. ISBN: 978-3-446-44526-0. (In German).

Österreichische Holzhandelsusancen (2006). [Austrian timber trade practices]. Service-GmbH der Wirtschaftskammer Österreich; Wien. ISBN-13: 978-3902110565. (In Germany).

Ouhimmou, M.; D'Amours, S.; Beauregard, R.; Ait-Kadi, D.; Chauhan, S. Singh (2008): Furniture supply chain tactical planning optimization using a time decomposition approach. In *European Journal of Operational Research* 189 (3), pp. 952–970. DOI: 10.1016/j.ejor.2007.01.064.

Rauch, P.; Gronalt, M. (2010): The Terminal Location Problem in the Forest Fuels Supply Network. In *International Journal of Forest Engineering* 21, 2010 (2), pp. 32–40.

Rohde, J.; Meyr, H.; Wagner, M. (2000): Die Supply Chain Planning Matrix. In *PPS Management* (5), pp. 10–15.

Saghiri, S. (2011): A structural approach to assessing postponement strategies. Construct development and validation. In *International Journal of Production Research* 49 (21), pp. 6427–6450. DOI: 10.1080/00207543.2010.531774.

San-Miguel-Ayanz, J.; Rigo, D. de; Caudullo, G.; Durrant, T. H.; Mauri, A. (2016): European Atlas of Forest Tree Species. 2016th ed. Luxembourg: Publication Office of the European Union.

Schnetzler, M.; Lemm, R.; Bonfils, P.; Thees O. (2007): Das Supply Chain Operations Reference (SCOR)-Modell zur Beschreibung der Wertschöpfungskette Holz. English: The Supply Chain Operations Reference (SCOR)-Model to describe the value-added chain in forestry. In *Allgemeine Forst und Jagdzeitung* (180. Jg., 1/2).

Seidl, R.; Schelhaas, M.J.; Lexner, M. J. (2011): Unraveling the drivers of intensifying forest disturbance regimes in Europe. In *Global Change Biology* 17 (9), pp. 2842–2852. DOI: 10.1111/j.1365-2486.2011.02452.x.

Song, G.; Sun, L. (2016): Evaluation of factors affecting strategic supply chain network design. In *International Journal of Logistics Research and Applications* 20 (5), pp. 405–425. DOI: 10.1080/13675567.2016.1267125.

Supply Chain Council (2008): Supply Chain Operations Reference Model. SCOR Overview Version 9.0.

Tani, G.; Cimatti, B. (2008): Technological Complexity: a Support to Management Decisions for Product Engineering and Manufacturing. In *IEEM 2008 The IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 6–11.

Teischinger, A. (2019): Zur Laubholzfrage in Österreich Eine Zusammenstellung aktueller Entwicklungen und Aktivitäten in Österreich und im benachbarten Ausland. [The hardwood question in Austria. A compilation of current developments and activities in Austria and neighbouring countries]. Lignovisionen (34). (In German).

Temponi, C.; Yen, J.; Tiao, A. (1999): House of quality: A fuzzy logic-based requirements analysis. In *European Journal of Operational Research* 117 (2), pp. 340–354. DOI: 10.1016/S0377-2217(98)00275-6.

Thompson, M. K., Stolfi, A., Mischkot, M., (2016): Process chain modelling and selection in an additive manufacturing context. CIRP. Journal of Manufacturing Science and Technology. Vol 12. pp. 25–34. DOI: 10.1016/j.cirpj.2015.09.005.

Toivonen, R. M. (2012): Product quality and value from consumer perspective—An application to wooden products. In *Journal of Forest Economics* 18 (2), pp. 157–173. DOI: 10.1016/j.jfe.2011.12.004.

Torno, S.; Knorz, M.; van de Kuilen, J.-W. (2013): Supply of beech lamellas for the production of glued laminated timber. In *4th International Scientific Conference on Hardwood Processing*, pp. 210–217.

Valverde, F.; Daniela, P. (2019): Improving efficiency in logistics operations of the wood fiber supply chain. Master Thesis: Virginia Tech.

Verkasalo, E.; Heräjärvi, H.; Haapala, A.; Möttönen, V.; Brännström, H.; Vanhanen (2017): Current and Future Products as the Basis for Value Chains of Birch in Finland. *ISCHP 2017. 6th International Scientific Conference on Hardwood Processing*. pp. 69–80.

Vila, D.; Martel, A.; Beauregard, R. (2006): Designing Logistics Networks in Divergent Process Industries: Methodology and its Application to the Lumber Industry. In *International Journal of Production Economics* (102), pp. 358–378. DOI: 10.1016/j.ijpe.2005.03.011.

Waller, M.; Dabholkar, P. A.; Gentry, J. J. (2000): Postponement, product customization, and market-oriented supply chain management. In *Journal of Business Logistics* 21, pp. 133–159.

Walther, G.; Schatka, A.; Spengler, T. S. (2012): Design of regional production networks for second generation synthetic bio-fuel – A case study in Northern Germany. In *European Journal of Operational Research* 218 (1), pp. 280–292. DOI: 10.1016/j.ejor.2011.09.050.

Westlund, K.; Furness-Lindén, A. (2010): Scrutinizing the wood supply chain - reporting from work in progress. FORMEC 2010 - Forest Engineering: Meeting the Needs of the Society and the Environment. Padova, Italy, 2010.

Wilhelms, F.; Bollmus, S.; Schlotzhauer, P.; Militz, H. (2017): Drying of low quality birch timber – quality, time and energy consumption. In *ISCHP 2017: 6th International Scientific Conference on Hardwood Processing*, pp. 297–303.

Wolfsmayr, U.; Rauch, P. (2014): Primary forest fuel supply chain: assessing barriers and drivers for the modal shift from truck to train. In *Silva Fennica* 48 (5). DOI: 10.14214/sf.1217.

Zanjani, M. K.; Ait-Kadi, D.; Nourelfath, M. (2013): A stochastic programming approach for sawmill production planning. International Journal of Mathematics in Operational Research. 5(1):1–18.

7. List of Figures

8. List of Tables

9. List of Abbreviation

HoQ	House of Quality
LBWSN	Laminated Beech Wood Supply Network
LBWF	Laminated Beech Wood Facility
MILP	Mixed Integer Linear Programming
PTM	Process-Technology Matrix
QFD	Quality Function Deployment
SND	Supply Network Design
VSM	Value Stream Mapping

ACPS	Sycamore maple
BTXX	European birch
CPBT	Hornbeam
EUGL	Eucalyptus
FASY	European beech
FXEX	Eruropean ash
JGXX	European nut tree species
QCXE	European oak
POXX	Poplar species
PRAV	European cherry

10. Conference contributions

10.1. Oral presentations

• 2015/Sep/15 – 17th	ISCHP 2015 – 5th International Scientific Conference on Hardwood Processing – Québec, Canada
• 2016/Aug/22 – 25th	WCTE 2016 – World Conference on Timber Engineering – Vienna, Austria
• 2017/Jun/12 – 16th	IUFRO 2017 – Division 5 Conference - Forest Sector Innovations for a Greener Future – Canada, Vancouver

10.2. Poster presentations

• 2014/Sep/15 – 18th	IAWS & Hardwood Conference 2014 - "Eco-efficient Resource Wood with special focus on hardwoods" – Sopron, Hungary & Vienna, Austria
• 2015/Aug/19 – 21st	SSAFR 2015 – 16th Symposium for Systems Analysis in Forest Resources – Uppsala, Sweden
• 2015/Oct/5 – 6th	WSE 2015 – 1st International Scientific Conference WOOD – SCIENCE – ECONOMY – Poznan, Poland

11. Appendix Publications

Paper I

Kühle, S; Teischinger, A; Gronalt, M (2016): Structure analysis of a production network by means of quality function development and values stream mapping.

World Conference on Timber Engineering (WCTE 2016). Vienna, August 22-25, 2016.

In: J. Eberhardsteiner, W. Winter, A. Fadai, M. Pöll, (Eds), CD-ROM Proceedings of the World Conference on Timber Engineering (WCTE 2016); ISBN: 978-3-903039-00-1

WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

STRUCTURE ANALYSIS OF A PRODUCTION NETWORK BY MEANS OF QUALITY FUNCTION DEVELOPMENT AND VALUE STREAM MAPPING

Sebastian Kühle[1], Alfred Teischinger[2], Manfred Gronalt[3]

ABSTRACT: The purpose of the paper is a conceptual framework to analyse supply chain networks by providing information. The approach uses the Quality Function Deployment (QFD) and Value Stream Mapping (VSM) methodology for a better understanding of the interaction and reaction of upstream and downstream companies in the supply chain network. The focus is on products, process chains and related technology. For this purpose quantitative and qualitative information is necessary. We using two methods and combine them to analyse the network from two directions. The QFD starts from the customer and product side - the so called customer view. The VSM focuses product´s manufacturing life cycle. The approach is applied to the solid hardwood production network as case study. The expected result is a procedure to evaluate systematically the actual network on resource-efficient capacity utilisation as well as redundant and limiting process chain elements.

KEYWORDS: Quality Function Deployment, Hardwood, Supply Chain Network, Technology, Process Chain Elements, Value Stream Mapping

1 INTRODUCTION

Hardwood industry faces major challenges in Europe and beyond [1, 2, 3]. It has to find its stability and market place once again. The increasing hardwood timber stock in forest is still in contrast with a stable slightly decreasing utilisation in the wood-based [1]. A gap is evolving between resource growth and material utilisation. One reason for the issue concerns the missing links in the supply chain (SC) from to product and customer or it is better to say that the intransparent links and supply chain network lead to complexity [3, 4]. Those links and activities essential parts of a supply chain network (SCN). SCN members produce products step by step (
Figure 1). Every single manufacturing and processing step within SCN chances the quality of the ready-made product. Each business, which is involved in the product transformation process, is responsible for the product quality.
[4] describe different aspects where complexity occurs within SC and focuses on global sourcing. There are interesting ideas mentioned which are also issues for companies which act nationally or cross-nationally. Although, companies act nationally, competitors are located global nowadays. Inefficient SC can relate from complex SC structures or product design. The focal company may not have production quality problems. The problems can also be traced back to the upstream stakeholders.

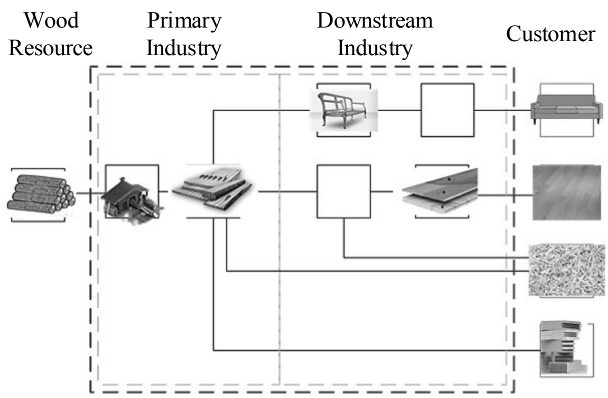


***Figure 1:** Selectet dependant supply chain network and process steps. The primary industry provides the downstream manufacturings with intermedia products. The system boundary relates to the inter business links between wood resource to sawmill and produced finished products from the downstream manufacturer to customer.*

The hypothesis is that information provision about the supply chain structure provides knowledge which leads to an increase of efficiency by SC structure optimization. Within the SC and process chain, transparency relates on the one hand to insight considering the match of adjoins process chain elements but also to correlated technology. Thus, the process chain elements bridge a link from product design to technology.

[1] Sebastian Kühle, BOKU - University of Natural Resources and Life Sciences, Vienna, Institute of Wood Technology and Renewable Materials, skuehle@boku.ac.at
[2] Alfred Teischinger, BOKU - Institute of Wood Technology and Renewable Materials
[3] Manfred Gronalt – BOKU - Institute of Production and Logistics

Our approach uses the Quality Function Deployment and Value Stream Mapping methodology for a better understanding of the interaction and reaction of upstream and downstream companies in the SCN and their specific process functions.
For this purpose the paper is organized as follows: First the scope of the paper is given. The literature review in chapter 2 contains both tools and describes their basic functions. Additionally, both methodologies are considered to the research field of SC and their application. After that, chapter 3 illustrates the specific guidelines for the conceptual framework which forms the innovative approach. Chapter 4 gives a summarised overview of the case study. Chapter 5 concludes the paper.

2 LITERATURE

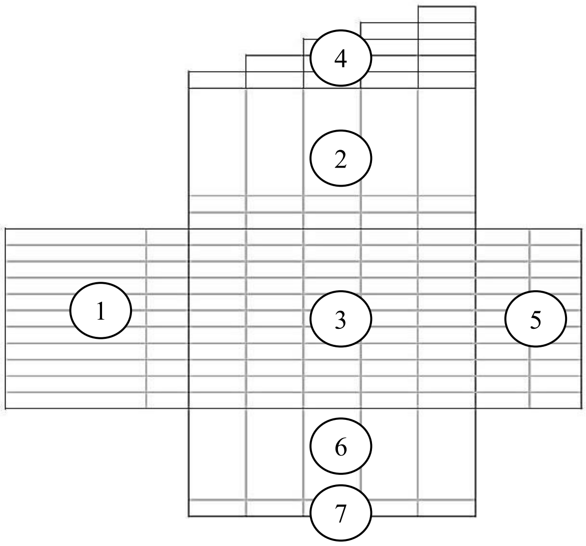
2.1 QFD

2.1.1 What is QFD?

Yoji Akao, developer of QFD, defines QFD as planning and development tool for quality functions of a product, which are requirement from customer as quality characteristics. The ASI (American Supplier Institute) goes one step further and specifies the definition. By companies, customer requirements have to transform into internal production potentials. These potentials have to be reflected on products development phases from product design up to product launch. [5] indicates that the application of QFD has a framework procedure but the task in each step cannot divided into subtask and completed in corresponding departments. QFD lives from cross-division collaboration and hence QFD receives its success. Thus, the two main functions of QFD are customer orientation and teamwork.

2.1.2 Benefits

The core of the Quality Function Deployment is formed by customer requirements for a selected product. Its ultimate objective is the satisfaction of the customer. With regard to the supply chain – even though the product/customer is the last element in the supply chain or the first – its ultimate objective is the fulfilment of customer demands in quantity and quality. The HOQ is the tool of the QFD which meets these requirements. It is a conceptual scheme and guides the user through the procedure to develop the QFD. The main function of the HOQ is a matrix correlating two different attributes. The general procedure includes particular components and forms a recognisable shape (*Figure 2*). It helps to transform customer requirements into internal characteristics. It is similar to a utility analysis. In both cases you use a liker scale to compare different physical units with subjective background of the user. But compared with a utility analysis it has addition functions. At first you do not compare criteria class 1 with criteria class 1. Instead you compare customer requirements (information class 1) with internal product characteristics. These are transformed information which depends on company´s resources and measurable product characteristics. And second the user develops the matrix with objectives. These objectives are mostly quantitative, technical data like ranges of length or speed.



1) “**What**”– Customer Requirements
   Voice of Customer
2) “**How**” – Engineered Product Characteristics
3) “**How vs. What**” – Interrelation Matrix
   How much supports “How” the “What”
4) “**How vs. How**” – Technical Correlation Matrix
5) “**Why**” – Assessment Matrix of contestant
6) “**How much**” – Determination of technical targets
7) **Priority of “How**”

Figure 2: *The general House of Quality*

Every part of the house has its reason and the user has to fill it with life in form of quantity or quality information. Furthermore, basic sections are benchmark and a technical correlation matrix which shows possible technical difficulties. The latter is often used in combination with TRIZ.
With a multi-step QFD approach the user reveals cross-functional information. We use the approach from Macabe and ASI [6, 7]. The structure is hierarchical and contains of four phases which are executed successively. The four phases are divided into product, component and process planning as well as process execution (*Figure 3*). Each phase is represented in a chart which correlates the requirements (“what”) with its implementation (“how”). In the following level, the former implementations are transferred as requirements. Therefore, the multi-step approach ensures a systematically development. A detailed description of the multi-step execution is shown in [7].

2.1.3 Limits

The QFD method has a critical deficit why decision maker or manager use it just once. At the early stages, it requires more time. Also, it should occupy time periods from heads of division. The combined company knowledge results in progressive solutions and pre-determined quality and process parameter. Principally, the unavoidable time expenditure at the beginning and the resource binding follows in decreased cost and post-processes at further steps.

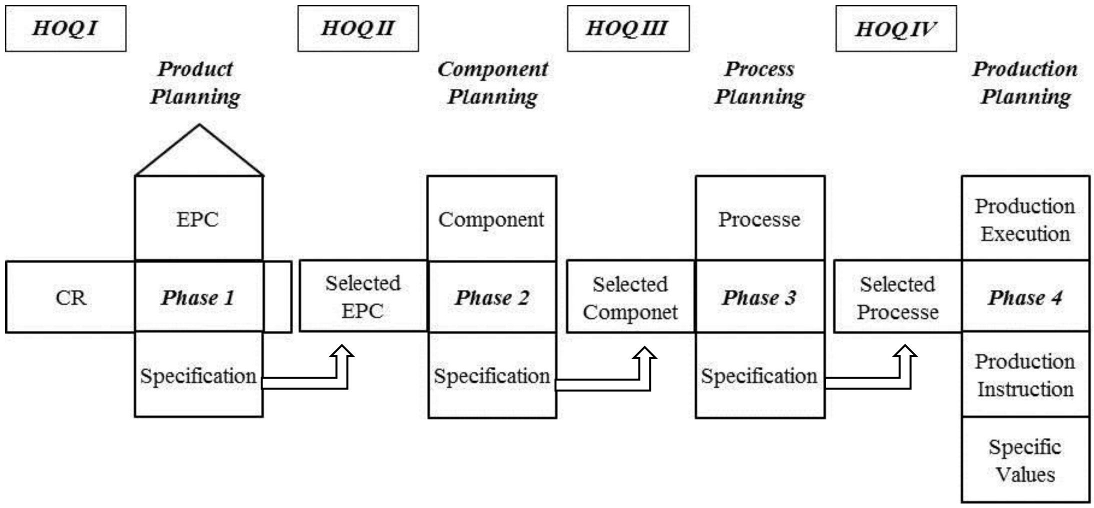


Figure 3: *The multi-step approach of the QFD*

Learning effects will decrease the expenditures and raise the yield. Thus, it is not the whole issue but the combination of time and inflexible, static adjustments brings up the crucial deficit. If the user modifies some requirements or internal characteristics, he has to adjust all effected parts all the way down. Due to QFD is an iterative process adjustments are inevitable.

2.1.4 Recommendation

The authors recommend for comprehensive information about QFD like procedure, application, performance [5], detailed explanation of the several house parts and the multi matrix approach [6, 7] , objectives [8], [9] and the classic review from [10].

2.2 VSM

2.2.1 What is VSM?

VSM is a tool of lean manufacturing, originates from the Toyota Production System [11], that helps to understand material and information flow as products make their way through value stream. VSM enables the allocation of specific data to each process chain element in the company. The value stream includes the value adding (internal production) and non-value adding (purchase, order and supply) activities that are required to bring a product from raw material through delivery to the customer.

VSM is a documentation tool and maps material and information flows from the raw material over the transformation processes to the customer at the operational level [12]. VSM is a draft of a product´s manufacturing life cycle which perceives all phases throughout the production process. The goals of VSM are to observe material flow in real time from the final customer to the raw material and to visualize losses in the process. The methodology consists of visualization, analyzing and optimization of the product´s manufacturing life cycle (PMLC). Three steps lead to a leaner manufacturing process. First it is examined the current status – value stream analysis. Modern companies have a wide product catalog, thus product families are used to follow their production stream. Then it is designed a target state of the production process – value stream design. The last step is to develop a program of measure to achieve the future state. The method targets at a lean, dynamic and customer controlled value stream, with short lead time and reduced inventories [8, 9]. It is widely used in industrial practice.

2.2.2 Benefit of VSM

The VSM enables the allocation of specific values to

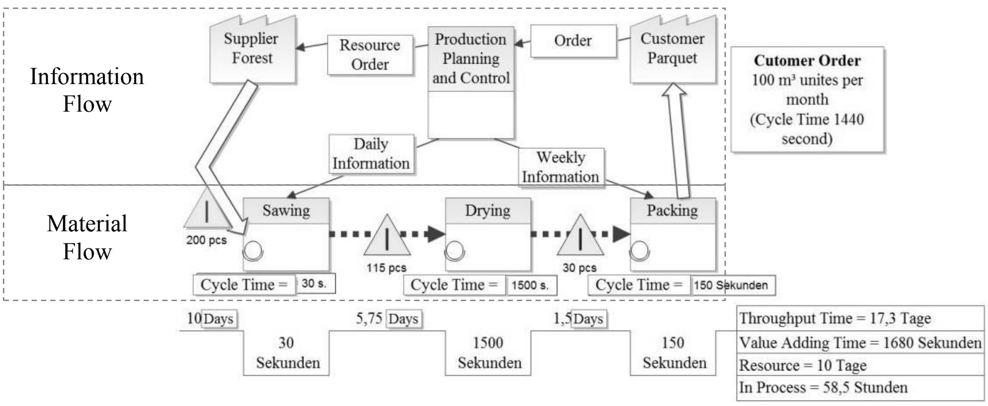


Figure 4:*Value Stream Map example*

each process chain element in the company. It is recommended to go the product manufacturing cycle. For the person, who maps the process, it is necessary to get an objective data base. Production manager calculate with specific data which often reflect not the reality. This fixed data developed over time and now it belongs to daily structure. The first optimization potential arises due to the gap between fixed process data and real process data.The intertwined material flows with the associated individual work station of the component as well as the products will be disentangled and systematically mapped Gathered transparency at the shop floor is premise for production optimisation. The representation of technical processes, materials and information flow with corresponding specific data shows the linkage between the production processes and their controlling information flows [13]. The VSM tool helps to consider the product manufacturing cycle as a whole. It is more than the sum of the individual parts. Specific business knowledge and experience links the parts to an efficient production line [14].

On the organisational level VSM provide a common language and learning effect [12]. The mapped processes and corresponding information are described with fixed terms.

2.2.3 Limitation

In their literature research, [15] identify eleven categories of problems during VSM implementation. They establish a guideline from the analysis of the causes. The considered issues have their core in the usage of the VSM method which are linked to the companies´ production concepts. VSM can be effectively applied on linear process chains. Divergent material flows, like wood disintegrating processes, have to consider separately. Parallel downstream processes are not possible to draw or would not show their influence. A recipe is to build product families. A product family is a grouping of products which start at similarities in resource over manufacturing processes and up to geometrical dimensions. Another main weakness point is general one. Limitation relates to the level of knowledge of the employees. In this case it would be a lack of training in basic lean concepts which helps mapping the products manufacturing cycle but not the development of a future state [16].

2.2.4 Recommendation literature for VSM

The authors recommends for comprehensive information about VSM and products development [17]. Their paper focuses on decreasing the time of product development process which takes around four to five years. They provide a comprehensive strategy to implement VSM as lean management tool in the process. At the beginning, they use pareto analysis to identify the top portion of causes which need to be addressed to resolve majority of problems or time consuming factors. [18] study the quality issue of a process chain and call it Quality Value Stream Mapping (QVSM). The procedure of QVSM helps to increase the transparency of quality control in process chains by considering present quality defects, quality inspections and quality control loops.

2.3 QFD + VSM FOR A SC OR SN

QFD and VSM are widely used regarding the methodologies as management tool for decision makers in single companies. Both consider complexity as long-term strategy. With QFD, the user looks at the complexity of the product structure within a company and takes it apart. This decreases the complexity by a multi-step procedure and develops systematically step by step a link between product and production planning as well as quality planning. This procedure achieves possibilities for optimisation strategies. With VSM, the user looks at the complexity of the process chains of the internal production.

[19] use QFD to connect manufacturing with cross divisional strategies to overcome the gap between diverse strategy directions in several divisions. Their approach provides a systematic tool to simplify strategy formulation. With a modified multi-step approach they realize the connection of manufacturing strategy with action plans. But with this modification, they lose the connection to the product and design. To some extent, complexities within business strategy arise from highly unintegrated business functions due to an intricate product design. Hence, issues occur in supply, demand, destitution and sailing.

Furthermore, scientific papers propose different approaches to tackle specific problems of the SC with QFD like supplier selection [20] [21], supply logistic planning [22], logistic service [23]. [24] focus on the main objective of SC management – fulfilment of customer needs. The authors see business resources, facilities as well as business functions including transportation, distribution,

Inventory and work force support the fulfilment process. Competitive strategies which consider these factors and aim to meet the customer needs will increase the business position. Therefore, they use in the first HoQ business competition strategy (customer requirements) correlated to supply chain design strategies (engineered product characteristics).

So far, QFD is used as management tool to work out products designs or supply chain strategies which consider customer needs. But, the literature does not provide any study that incorporates with the analysis of process chains for product manufacturing and the interrelated technology in an SCN environment. QFD makes it possible to ground the base for supply chain optimisation. Usually, QFD is a product development tool with quality management integration. The systemic procedures enable the product disassembly up to detailed production planning. Through comparing the optimised process chain with the current manufacturing process chain the scope of optimisation potential will be revealed also over business borders. The following methodology section will present the conceptual framework to analyse the process chain of a SC with QFD and SCM.

3 METHOD

Analysis methodologies require an extensive generation of information and presentation possibilities. For the qualitive and quantitive analysis of SCN instruments are needed as they guarantee a structured and consistent implementation of the actual state and performance of their actors. The linchpin of this method is the application of the multi-step QFD approach towards the several semi-finished and final products of the supply chain. The general workflow is illustrated in *Figure 5*.

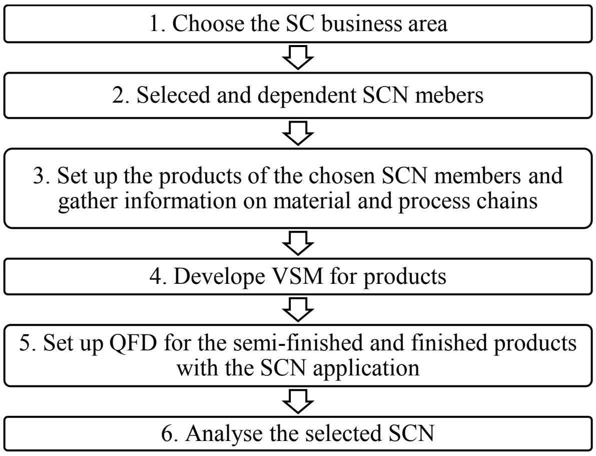


Figure 5: *Workflow for supply chain network analysis*

The following part describes modifications and instructions which affect the input and output factors of the multi-step QFD procedure to guarantee cross-company functional analysis.

Contrary to the general ultimate objective of the QFD it should be considered that the approach changes from a methodical product planning and development methodology to a supply chain analysis methodology based on the semi-finished and final products of the particular member. Consequently, four determinations need to be considered when using QFD.

At the time of consideration, the given products are used to represent the objective direction. The products implicate the market and customer requirements at the current point of time. Therefore, the voice of the customer is an obsolete input factor. Requirements that represent the business objectives of the various members are crucial for the SCN input. The input criteria design the solution space and have to apply to all supply chain members. According to [25] functions of The Iron Triangle (quality, time and cost) determine the solution space. At the initial implementation of the multi-step procedure the EPC of the HOQ I can be defined by focusing on the semi-finished or final products of the particular member.

Another determination affects the component planning in the HOQ II. In compliance with the amount of product components functions have to be attributed to the individual component. Components without functions are obsolete. Hence, it is guaranteed that each component is considered in the following HOQ III and HOQ IV.

A further determination is related to the production execution (HOQ IV). In contrast to the general development of the production characteristics, which should relate to the result of the HOQ III, fixed process chain elements (PCE) are used. A PCE is regarded as a transformation action whose output material is the input material of the next transformation action. The sum of the single PCE forms the process chain (PC) of a specific product (*Figure 6*). Thus, the PC of the given semi-finished or final products of the particular SCN member is used as the production characteristics of the HOQ IV. Each individual process in the manufacturing and processing industry can be documented with specific values like tool dimensions, material dimension, processing speed or cycle time. At this point an extensive performance recording takes place, which requires production engineering background that is not possible with just QFD.

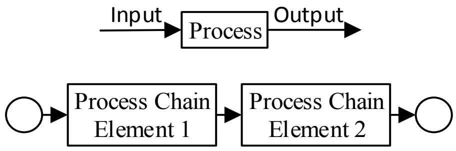


Figure 6: *Transformation process and simplified production process chain.*

Therefore, VSM is integrated. The value stream mapping (VSM) enables the allocation of specific values to each PCE in the company. The intertwined material flows with the associated individual work station of the component as well as the products will be disentangled and systematically mapped. After the execution of the integrated VSM tool two ways of evaluation are possible. One way uses current methodologies for analysing VSM. Primarily, approaches lead to identifying, quantifying, minimizing or eliminating wasted processes. According to [26] root cause analysis are necessary because VSM is just an analysis method to determine the actual state. [9] is recommended for analytically solve of core problems. The other way uses the VSM results for QFD network analysis as information carrier. VSM separates material and information flows into individual pieces. These pieces represent the single PCE with current dedicated technological parameters. The crucial information is transferred into HOQ 4. The modified QFD is the QFD with the supply chain oriented determination plus the integrated VSM.

The ultimate objective of functional depend information retrieval in SCN can be achieved by the consideration of the above mentioned determinations and instructions.

So far, there are two types for the assessment and utilisation of the QFD charts regarding the chosen products of SCN. The former takes into account the PCE. It analyses the redundancy. We use a process matrix for this purpose. It visualises the PCE along the SC so that redundant processes can be identified easily. The latter considers the functional dependency. The user of the QFD in SCN has to tailor the functions according to the individual operational business area. In the manufacturing and processing industry operators of the QFD in SCN develop product-based functions. These refer primarily to the material properties which are processed through manufacturing engineering processes like forming, separation or assembly. For example, if the user establishes the EPC attribute `surface quality´ in the HOQ I and transfers it to each component in the HOQ II, it is possible to identify the current dependent influencing parameter for the surface quality.

4 CASE STUDY AND PRELIMINARY RESULTS

So far, the conceptual framework is established. Different supply chains and process chains are disassembled if possible. A comprehensive evaluation has not been done yet. The following part represents the current heavily summarised results of the approach. *Figure 7* illustrates the progress overview on the basis of the above given execution procedure.

1. Choose the supply chain business area	Done
2. Select linked and dependent SCN members	Done
3. Set up the semi-finished and finished products of the chosen SCN members and gather information on material and process chains	Done
4. Set up QFD for the semi-finished and finished products with the SCN applications	Done
5. Set up VSM for the semi-finished and finished products	Not Done
6. Analysis of selected SCN	20%

Figure 7: *Progress of the hardwood SCN analysis*

For the application of the modified QFD methodology for SCN we chose several process chains of the solid hardwood processing industry. The primary industry is the sawmill. Based on the sawmill semi-finished products we selected the dependent downstream industries with their process chains (figure 8). The system boundary frames our contemplation space of the SCN. In the beginning the input parameters into the sawmill limit the system and at the end the output parameters from the downstream manufacturer, primary the product, limit the system.
After defining the system boundary, the combination of information about the several supply chains and the execution of the VSM (*Appendix I*) leads to the modified SCN QFD. We transferred the crucial information in the HOQ IV and got a high density of specific process values (*Appendix II*). The production part of HOQ IV include the crucial PCE. The example in the Appendix I represents the HOQ IV for a prefinished hardwood floor. Each column illustrates one PCE. The specific values for each PCE can be recorded at the bottom section. We gathered specific values to attributes like several times, dimensions, wood moisture and yields. It is possible to modify the section according to the type of production and necessary values.

5 CONCLUSION

The purpose of this paper was to present a new approach for gathering and analysing information of a SCN. The study was based on quality functions which are run throughout the downstream manufacturer up to the primary industry. Additionally, we wanted to provide the practical user with a ready-to-use tool. It was found that in order to design an efficient hardwood production network, extensive structured, filtered and analysed information is necessary to increase transparency and to raise efficiency in the decision making progress.
Results compare practical data from VSM with the detailed data from the multi-step QFD procedure. Both methodologies are approaches to consider product manufacturing life cycle in an even more holistic way. The information of the PMLC is collected over a plurality of sources which are connected to the product like the different technologies and specific machines. Linked processes can be analysed systematically
Currently, the hypothesis cannot be confirmed or denied.

6 ACKNOWLEDGEMENTS

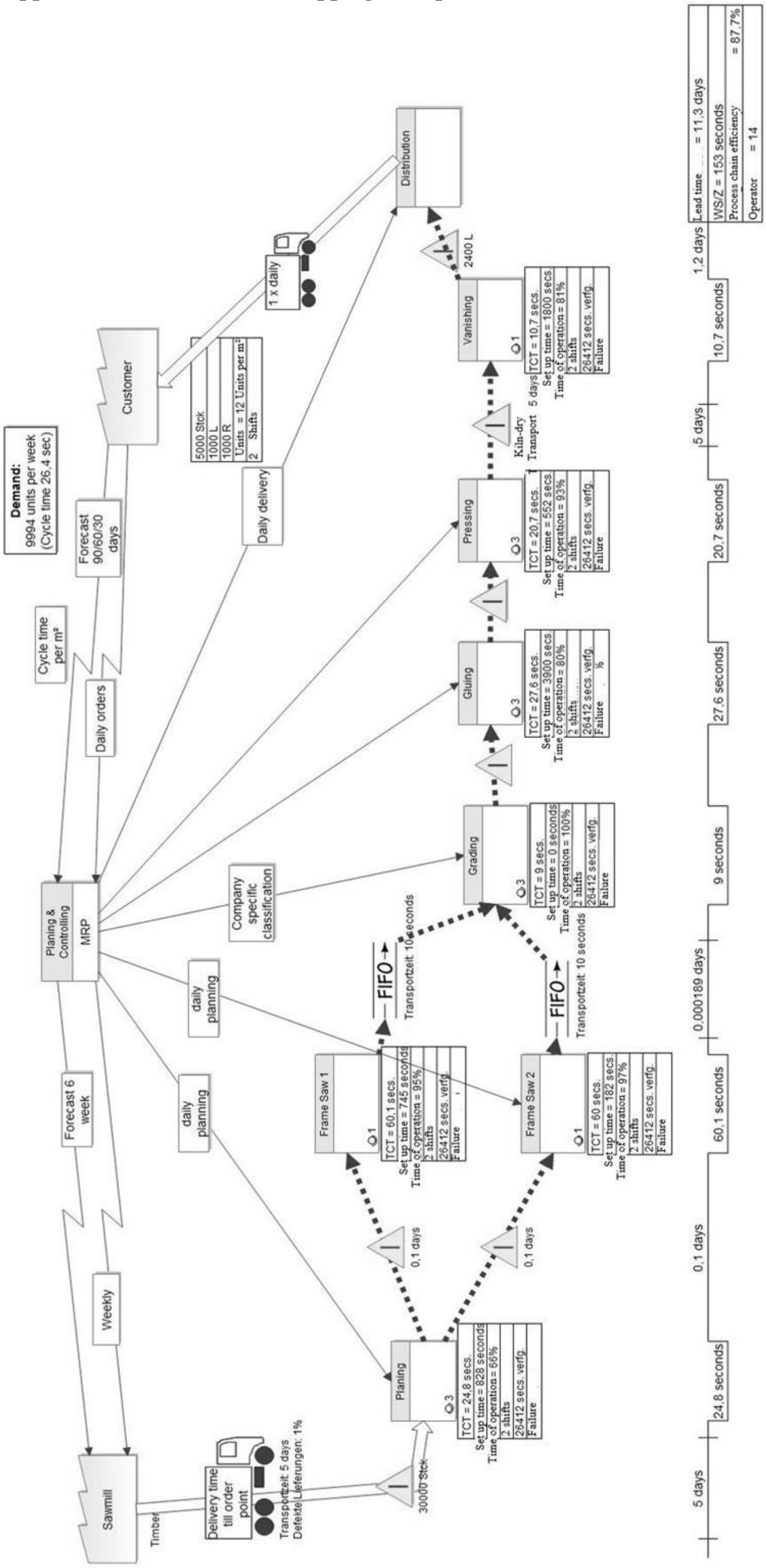
Financial support for this work in the framework of the PhDSchool DokIn´Holz funded by the Austrian Federal Ministry of Science, Research and Economy as well as the Austrian Federal Forestry Office and the Austrian Chamber of Agriculture are gratefully acknowledged.

7 REFERENCES

[1] Krackler, V., Keunecker, D., Niemz P., Hurst A: Possible Field of Hardwood Application. 2010th ed. The 5th conference on hardwood research and utilisation in Europe 2010.
[2] Sandberg D, Johansson J: New products and production systems for increased profitability within the mechanical hardwood industry. Creation of Industrial Competitiveness CIC:75–92.
[3] Howe J, Bowyer J: REINVENTING THE HARDWOOD INDUSTRY ONE COMPANY AT A TIME 2007.
[4] Gunasekaran A, Subramanian N, Rahman S: Supply chain resilience: role of complexities and strategies. International Journal of Production Research 2014;53(22):6809–6819.
[5] Saatweber J: Kundenorientierung durch Quality Function Deployment: Produkte und Dienstleistungen mit QFD systematisch entwickeln. 3rd ed. Düsseldorf, Symposion Publishing GmbH,, 2011.
[6] Mai C: Effiziente Produktplanung mit QFD, 1998.
[7] ASI: Quality Function Deployment: 3 Day Workshop. Dearbon, Michigan, 1989.
[8] Shahin A: Quality Function Deployment: A Comprehensive Review 2002.
[9] Oke SA: Manufacturing Quality Function Deployment: Literature Review and Future Trends. EJ 2013;17(3):79–103.
[10] Hauser JR, Clausing D: The House of Quality. Harvard Business Review 1988.

[11]Ōno T: Toyota production system: Beyond large-scale production. Cambridge, Mass., Productivity Press, 1988.
[12]Rother M, Shook J: Learning to see: Value stream mapping to create value and eliminate muda; a lean tool kit method and workbook; version 1.2. 1999th ed. Brookline, Mass., The Lean Enterprise Institute, 1999.
[13]Erlach K: Wertstromdesign: Der Weg zur schlanken Fabrik. 1st ed. Berlin, Springer, 2007.
[14]Klevers T: Wertstrom-Mapping und Wertstrom-Design: Verschwendung erkennen - Wertschöpfung steigern. 1st ed. München, Mi-Wirtschaftsbuch, 2009.
[15]Forno, Ana Julia Dal, Pereira FA, Forcellini FA, et al.: Value Stream Mapping: a study about the problems and challenges found in the literature from the past 15 years about application of Lean tools. Int J Adv Manuf Technol 2014;72(5-8):779–790.
[16]Serrano Lasa I, Ochoa Laburu C, de Castro Vila, Rodolfo: An evaluation of the value stream mapping tool. Business Process Mgmt Journal 2008;14(1):39–52.
[17]Tyagi S, Choudhary A, Cai X, et al.: Value stream mapping to reduce the lead-time of a product development process. International Journal of Production Economics 2015;160:202–212.
[18]Haefner B, Kraemer A, Stauss T, et al.: Quality Value Stream Mapping. Procedia CIRP 2014;17:254–259.
[19]Crowe TJ, Cheng C: Using quality function deployment in manufacturing strategic planning. Int Jrnl of Op & Prod Mnagemnt 1996;16(4):35–48.
[20]Ni M, Xu X, Deng S: Extended QFD and data-mining-based methods for supplier selection in mass customization. International Journal of Computer Integrated Manufacturing 2007;20(2-3):280–291.
[21]Bhattacharya A, Geraghty J, Young P: Supplier selection paradigm: An integrated hierarchical QFD methodology under multiple-criteria environment. Applied Soft Computing 2010;10(4):1013–1027.
[22]Ahmed S, Haque M: SCM DESIGN FOR WATER DISTRIBUTION WITH QFD APPROACH. Issues in Information Systems 2007.
[23]Zhang S, Dong Y, Pei B, et al.: Research on the Optimization Method of Logistics Service Capacity Based on Dynamic QFD. In 2008 International Conference on Intelligent Computation Technology and Automation (ICICTA), pp 664–668.
[24]Prasad, D. K. G., Subbaiah VK, Rao NK: Supply chain design through QFD-based optimization. Jnl of Manu Tech Mnagmnt 2014;25(5):712–733.
[25]Atkinson R: Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria. International Journal of Project Management 1999;17(6):337–342.
[26]Rohac T, Januska M: Value Stream Mapping Demonstration on Real Case Study. Procedia Engineering 2015;100:520–529.

Appendix I: Value Stream Mapping example



Appendix II:

Prozess Flow		System																			
		Group		Top Layer (TL)											Production of Ready-Made Parquet				Finishing			
		Components		Parquet Frieze				Lamella			TS Production				Components Assembling							
		Prozess Elements		Conditioning				Lamella processing														
				Drying	Dimension			Rip Sawing - Seperationn														
			1	2	4	6	7	8	9	10			12	13	15	16	17	18				19
What Selected Processes		**How** Production Excecution (Process Characteristics)	Material Charge	Predrying	Material Charge	Trimming	Quality Control/ Amount of Recirculation [%]	Blade Thickness of Thin-Cutting Frame Saw / Cutting Tool Geometry	Visual Sorting / Error Control / Quality Control	Storage	TL Glue Application	TL Compressing	Killn Drying	Assembling Single Lamellas to TL	Filling Conti Press	Glue Application / Moulding Time	Putty Station	Killn Drying	Profiling / Formatting	Control	Packaging	Storage
		Process Typ (D -Dynamic, S - Static)	D/S	S	D/S	D	D	D	D	S	D	D	S	D/S	D	S	D	S	D	D	S/D	S
Nr.	**Process Characteristics**	**Objective Values**	**Value**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	Pre-Delivery Check / Dimension	Processing Moisture of the Company ~ 12%	4		3	1	3	3	3		3				3		9						
2	Planing + Trimming		2		3	3	9	9	1		3			3	1	1							
3	Seperation Facility	Thin-Cutting Frame Saw Stroke Rate and Rotational Speed	5		3	1	1	3	9		9			3	3	1							
4																							
						Menge/ Art/ Probleme	Maße	??? Welche Sensoren werden genutzt?	> 0,7 mm	Firmenfestlegung (Klassen, Anzahl, Qualitäten) Wie?													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Reslut: Internal Meaning		Absolute			33	15	35	45	59	0	63			21	29	7	27	0	0				0
		Relative			9,9%	4,5%	10,5%	13,5%	17,7%	0,0%	18,9%			6,3%	8,7%	2,1%	8,1%						
Time	Throughput Time						XXX	XXX	XXX	XXX				XXX									
	Cycle Time			XXX		XXX	XXX	XXX	XXX	XXX				XXX									
	Duration Time				XXX		XXX		XXX														
	Maintenance				XXX		XXX		XXX														
	Service Life				XXX	XXX					XXX			XXX									
Speed	feed rate [m/s]						XXX	XXX	XXX	XXX													
Maschinenbearbeitungsmaße/ Belegungskapazität	Height - max/min [mm]				XXX		XXX		XXX		XXX			XXX				XXX					
	Width - max/min [mm]				XXX		XXX		XXX		XXX			XXX				XXX					
	Length - max/min [mm]				XXX		XXX		XXX		XXX			XXX				XXX					
Workpiece Dimension	Height - max/min [mm]			XXX	XXX				XXX									XXX					
	Width - max/min [mm]			XXX	XXX				XXX									XXX					
	Length - max/min [mm]			XXX	XXX				XXX									XXX					
	Input [mm³]			XXX	XXX		XXX		XXX									XXX					
	Output [mm³]				XXX		XXX		XXX									XXX					
Wood Humidity	Input [%]			XXX	XXX																		
	Output [%]				XXX			XXX		XXX													
Maintenance Intensity/ Period	Days				XXX				XXX														
Connected Load [kW]					XXX		XXX		XXX														
Yield	Absolute			100%	95%		90%		70%									XXX					
	Relative to Raw Material [%]			100%	95%		86%		60%									XXX					

Paper II

Kühle, S; Teischinger, A; Gronalt, M (2019a): Connecting Product Design, Process, and Technology Decisions to Strengthen the Solid Hardwood Business with a Multi-Step Quality Function Deployment Approach. Bioresources 14(1): 2229-2255. DOI: 10.15376/biores.14.1.2229-2255.

Connecting Product Design, Process, and Technology Decisions to Strengthen the Solid Hardwood Business with a Multi-Step Quality Function Deployment Approach

Sebastian Kühle,[a]* Alfred Teischinger,[a] and Manfred Gronalt [b]

Hardwood is currently underestimated with respect to its utilisation and its value creation potential. Due to changes in forest management in various countries, hardwood resources will become more important. However, solid hardwood (SH) production capacities, mainly structured as small to medium-sized enterprises (SME), are dropping or have dropped already because of changes in the wood products market. Enhancing the SH sector, the foundation of products, processes, and technology must be better understood. To support the SME SH business, the approach used here focuses on manufacturing processes of the first and secondary downstream industry. A multi-step Quality Function Deployment has been developed to match the manufacturing process with the product architecture, and a Process-Technology Matrix has been added to visualize the influence of technology on the manufacturing process. Both have been applied on three chosen hardwood products which are solid wood panel, parquet, and glued-laminated timber. The main contribution of the paper is a conceptual consideration with a conceptual framework rather than providing comprehensive solutions. Optimization potential exists within the SH manufacturing chain based on alternative the combinations of manufacturing processes and applied technologies.

Keywords: Quality Function Deployment; Hardwood; Production Processes; Technology; Process-Technology Matrix; Structure Design

*Contact information: a: BOKU - University of Natural Resources and Life Sciences, Vienna, Department of Material Science and Process Engineering, Institute of Wood Technology and Renewable Materials, Konrad-Lorenz-Straße 24, 3430 Tulln, Austria; b: BOKU - University of Natural Resources and Life Sciences, Vienna, Department of Economics and Social Sciences, Institute of Production and Logistics, Feistmantelstraße 4, 1180 Vienna, Austria; *Corresponding author: skuehle@boku.ac.at*

INTRODUCTION

Due to the adoption of measures to deal with climate change and its causes, the share of hardwood resources has increased and there is an increase in the forest stock in central Europe (Berendt *et al.* 2017; BMLFUW 2015). On the other hand, the production and utilization of hardwood lumber in Europe have decreased in the last decades (Luppold and Baumgardner 2015).

There is a gap between increasing forest resources and the corresponding production capacities of solid hardwood (SH) (Krackler *et al.* 2011). Further, the product-process portfolio of the wood industries is challenging and complex because they are based on mixed wood species with a high variety. In order to narrow this gap and tackle the challenge, a systematic approach to disclose processing opportunities is required. For this, an integrated analytical framework, multi-step Quality Function Deployment (QFD), is developed and applied to representative products and related technologies.

Looking for New Products and their Architecture

Designs of products and manufacturing processes are strongly connected, which has been demonstrated by the product process matrix of Hayes and Wheelwright (1979). Subsequent studies have enhanced the concept of the two-dimensional perspective and integrated a third one – the supply chain. Researchers have found an overlapping influence of product, process, and supply chain, which has resulted in the three-dimensional concurrent engineering concept (3DCE) (Fine 2000). The method supports the integration of firm core competences to achieve competitive advantage. Product, process, and supply chain must be treated as a single, fully integrated capability and managed in parallel instead of as separate capabilities.

At this point, a simplification is proposed to render a complex subject more tractable. Instead of matching a product, process, and supply chain, this paper focuses on the aspect of product, manufacturing process, and the dependent technology (Fig. 1). Only when a certain processing step is to be carried out will it be considered which technology can be used for it and how it is related to the other processes and product components. The aspect hardwood supply chain is an important component and will increase, but it is not an essential part in this work. Since the increased interest in hardwood resources, much research in product development has been performed (Wehrmann and Torno 2015). However, there has been a lack of successful technology implementations.

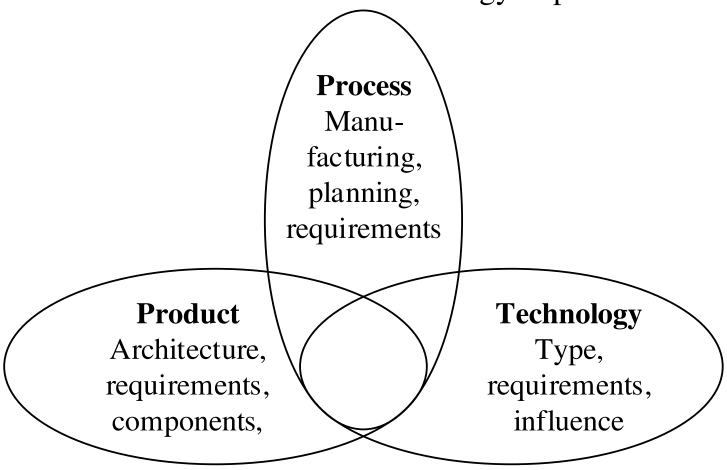


Fig. 1. The interlinked parameter product, process and technology are represented with further included aspects. The intersections show the links between two or all three aspects.

The Influence of Product Architecture on the Manufacturing Processes

The product's architecture has an essential influence on the manufacturing. It is related to the structure and components of the product. Product architecture is defined as "the basic physical building blocks of the product in terms of what they do and what their interfaces are to the rest of the device" (Ulrich and Eppinger 2015). It is a synergy of a tangible, physical product part and an intangible product part such as services or supplier related characteristics (Toivonen 2012). Each physical building block, in this work referred to as product components, has a specific function and is connected with further product components. The sum of the product components is the product. These components are produced by single chain of process elements. Appropriate selection and optimization of process chains is essential for product quality, process performance, and production efficiency (Thompson *et al.* 2016).

For hardwood, single manufacturing processes must be synchronized to the whole manufacturing process chain as well as to the depending technology. Due to the specific natural raw material, determined and controlled manufacturing concepts are required with defined production processes and related technologies. Thus, *e.g.*, wood moisture content is well managed within the downstream processes for high and stable product quality.

Technology and its Impact on Processes

Available technology has an impact on product architecture, possible process chains, as well as firm performance (Lin and Chang 2015). The technology must be economically viable to firms and it has to match the requirements on production capacity as well as the quality of the product. It is important that the technology supports its purposed manufacturing process and the adjacent processes.

Comprehensive knowledge is necessary to support this aspect because the technologies, which are used along the production chain from raw material to intermediate products, have a strong influence on the component's final properties (wood texture, colour, moisture content, strength, *etc*.). Therefore, specific methods are required to support the creation of a technological knowledge base and to support the identification of unknown cause-effect relations over the entire process chain.

Currently, a fast-growing development of new technologies and technology combinations can be recognized in the wood-based sector. These developments offer companies the opportunities to be more competitive in the marketplace in terms of time, cost, flexibility, or quality.

The relations between product architecture and manufacturing system, consisting of manufacturing process and technology, must be understood and managed during the design phases or during improvement processes. Existing links between both aspects represent how they affect each other. Changes in the products may require new technologies, and an additional process or a product may require improved changes to implement a more efficient manufacturing chain.

Approach Selection

With the focus on product development and quality management, Quality Function Deployment (QFD) helps to support the development of a long-term strategy. It translates customer requirements into technically specific data. Step by step, it links these subjective customer requirements with the rational design of the product and QFD supports multi-criteria decisions (Akao and Chan 2011).

Further, in order to analyze manufacturing process chains, it must be clear how many product components will be designed, how each component will be produced, and how each component and manufacturing process affects and is affected by the others as well as by the technology applied. For this purpose, a conceptual framework is developed based on an adapted multi-step QFD approach with an elementary Process-Technology Matrix (PTM).

The method visualizes the decomposition of the product as well as processes and gathers systematically the necessary characteristic data. The execution of the method needs low resource investments. The method supports a fundamental, cross-company decomposition of the product, which is an important element of this work. Also, the results of the QFD methodology support the identification of performance indicators and the determination of improvement priorities of the indicators (Franceschini *et al.* 2009).

For a far-reaching thematic consideration, it can be said that QFD is already used in a wood-based context. Melemez *et al.* (2013) used the tool to design a small timber trailer for small pieces of wood. Gusakova (2016) conducted a competitive analysis of biorefinery firm strategies with QFD as analyzing tool. Wolfsmayr and Rauch (2014) used QFD to identify barriers and drivers for the forest biomass supply with specific transport sequence types. Wagner *et al.* (2007) applied QFD to the Chilean wood-based industry to assess if the competitive advantages of the company stay in line with their customer needs.

In order to identify suitable hardwood species for a specific product, Neyses and Sandberg (2015) combine QFD and multivariate data analyses, which then are used for a structured, quantifiable, and easy-to-use methodology. By applying QFD to the SME wood-based network, Massa and Gessa (2016) aimed to achieve the improvement of the network partner collaboration, the product innovation in the supply chain, the product quality, the competitiveness in the market, the responsiveness to final user requirements, and to highlight the criticalities in the production process along the whole supply chain.

The literature shows that QFD supports the development of products, services, and strategies. It reveals that QFD is a qualitative and semiquantitative method with limitation. Several authors improve this situation by combining QFD with additional methods to reduce the limitation of QFD and to improve the final results. To the best of our knowledge it can be said that a multi-step QFD has not been used for setting up the framework to analyze processing potentials in the SH supply chain.

This paper aims to support developments in the SH business that require redesigning and revisiting of conceptual considerations. To achieve this objective, it examines the possibility of integrating product, manufacturing process data, and technology solutions into a systematic approach. The paper places emphasis on supporting these conceptual considerations with a conceptual framework more than providing comprehensive solutions to detailed designing of the product and manufacturing system and detailed manufacturing process planning. These results provide manager, practitioner and researcher with further information to prepare for new processing options.

METHOD

The method part comprises the development of the multi-step QFD process and the description of the Process-Technology Matrix. It finishes with the visualization of the two steps that build the conceptual framework.

The here presented conceptual framework with the two main steps is the product of an iterative process. Several feedback loops were used to develop the framework. First ideas and concepts were presented at dedicated conferences and industry expert meetings. Received feedback was used to improve the intermediate concepts up to the multi-step QFD approach presented here.

Quality Function Deployment - Using Customer Perspective

The core of the QFD is formed by the quality functions of a product. These functions are developed and planned with the help of the QFD. Quality functions are requirements of the customers and are integrated by the “Voice of Customer”. These requirements are transformed into feasible company quality characteristic (Akao 1990). By companies, customer requirements are transformed into internal production potentials - the product quality characteristics (PQC). These potentials have to be reflected in product development phases from product design up to product launch (Saatweber 2011; Hauser and Clausing 1988; Mai 1998). To develop and define PQC fitting to the customer requirements, a company´s product designer and engineer team lists those PQC that are expected to affect one or more input requirements (Table 1). If a PQC do not affect a requirement, it is redundant, or the team missed a customer aspect (Hauser and Clausing 1988).

The “House of Quality” (HOQ) is the tool of the QFD that supports the transformation process. Products, services, or processes are designed to meet customer demands. This is the foundation of the HoQ (Temponi *et al.* 1999). With a simple structure, the HoQ guides the user through the procedure to develop the QFD (Hauser and Clausing

1988; Wolfsmayr and Rauch 2014). The main function of the HOQ is a relationship matrix (RSM) that assesses the effect of PQC on customer requirements. The relation is given by graphical symbols that represent the numerical numbers 9, 3, 1, 0 or by the numerical numbers directly. The final result of the first HoQ is knowledge, which is provided by translating systematically the customer requirements into quality characteristics of the product or service by the firm's own capabilities. The knowledge is summarized by the HoQ. Subsequently, the house enables multifaceted correlation, which is visualized to support decision-making.

Originally, the PQC and RSM is populated by an inter-divisional team which consists of product planners, design engineers, manufacturing engineers, and salespeople to translate simultaneously the VOC and edit the matrix. Here, the RSM was populated by the authors with the support of the iterative process.

Multi-step Quality Function Deployment approach

In this study, the presented methodology uses the approach from Macabe and the American Supplier Institute (Hauser and Clausing 1988; Mai 1998). It is an often used approach to implement a multi-step QFD concept. In most cases one House of Quality (HoQ) was not sufficient to gather the critical quality functions. For a full quality and product development management, further HoQ units can be applied, which consider product components (HoQ II) as well as processes (HoQ III) and production planning (HoQ IV). The framework helps to look at the complexity of the product architecture structure and takes it apart. This decreases the complexity by a multi-step procedure and systematically develops a link between product and production planning as well as quality planning. The structure is hierarchical and comprises four phases, which are divided into product, component, and process planning as well as process execution. Each phase is represented in a chart which correlates requirements with its engineered characteristics. In the next level, the former implementations are transferred as requirements. Therefore, the multi-step approach ensures a systematical development.

Modifications are needed because contrary to the general ultimate objective of the QFD, it should be pointed out that the presented conceptual approach has an additional objective. Beside the methodical product planning and development, it also aims to support the analysis of product structure, manufacturing process chain, and linked technologies based on semi-finished and final products. The decision about product design, manufacturing processes and technologies are long-standing decisions and choices that impact the future. The quality assurance planning, maintenances as well as work instruction of the HoQ IV consist of mid- to short-term decisions that are strongly variable from the chosen product of the individual firm. Thus, for the presented approach the detailed, mention aspects are not used because of the conceptual consideration of this paper (Fig. 2). Instead of the HoQ IV, a PTM is added subsequently (next section).

A further adaption of the concept is related to the input information. Two possible ways are here suggested to start from the customer perspective. The first one is the traditional one and targets product and quality development. The input material is gathered by interviews, questionnaires, and market research in order to define the customer need. The employed tool depends on the possible firm resources. The second way implies that the focus is based on the three aspects of product, process, as well as technology and that they match properly. It already has been assumed that the product is designed to meet customer demands. If one uses the assigned requirements of a product that are part of the recent product portfolio, one ensures a level of product quality. The requirements are the already determined product components, in-house production steps, and applied technologies. This helps to go beyond the product development process of QFD and evolves to a general consideration of the production process at all. Additionally to the to the product improvement, a re-engineering of manufacturing process and applied technology are possible. Due to the intended conceptual considerations, it is suggested to use general requirements as input for this way. In this work, the second way is chosen. To guarantee an analogue procedure for the several products, the same requirements are defined for every single hardwood product considered - higher product quality, lower production cost, lower delivery time, higher material yield, and better design. With the developed procedure, it should guaranty that the product architecture with its components and functions matches the requirements (HoQ I, II) and that the manufacturing process matches the product components.

The same procedure is done for the selected component characteristics in HoQ II. Selected PQC are translated into technical component characteristics such as material quality or grain direction. The used information is provided by educated guesses, scientific papers and studies, interviews and discussion with experts, standardization committees, as well as wood-based interest magazines and brochures.

For HoQ III, standard wood-related manufacturing processes are used, which convert input raw material into a determined product (Wagenführer and Scholz 2018).

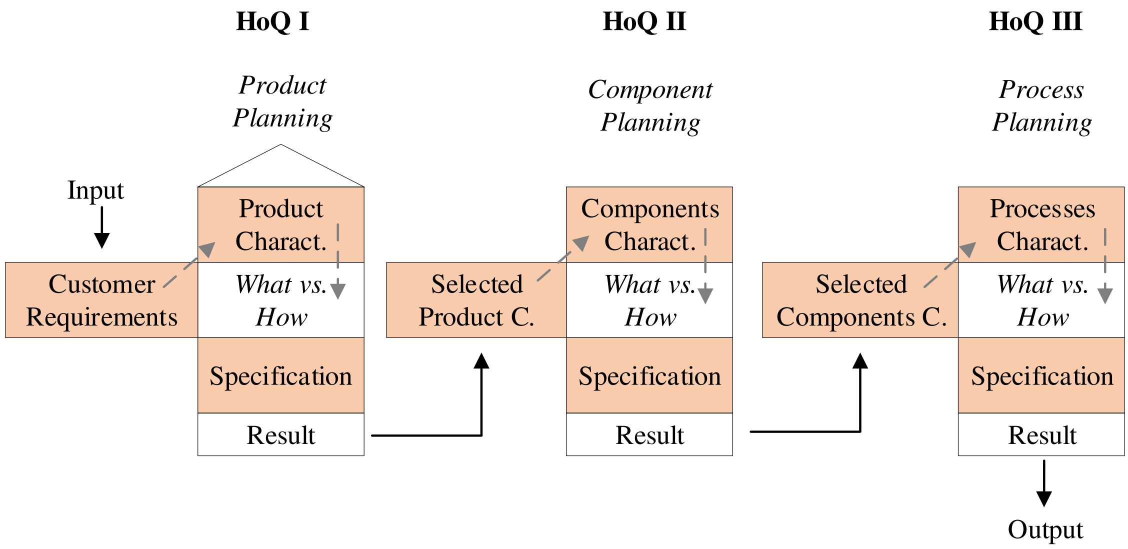


Fig. 2. The three House of Qualities are combined to the multi-step approach. The pre-defined requirements of the HoQ I are the initialization to develop the first HoQ. With the HoQ I relationship matrix, the user determined the influence of product quality characteristics on the pre-defined requirements. The illustrated specification section contains the PQC objectives and the evaluation part. The selected PQC of the HoQ I are included in the HoQ as input requirements for the component quality characteristics. Analogue to HoQ I, HoQ II and III are executed.

Process-Technology Matrix

Technology is a firm's key resource. It enables companies to develop products and to increase productivity Thus technology is linked with business performance (Lin and Chang 2015).

The standard QFD has no consideration of technology integration. Therefore, a PTM is added after the multi-step QFD approach. It represents the firm´s possibilities to execute their processes with various existing technologies or modified machines. The procedure is adopted from the direction and function of the RSM of a HoQ. Instead of rating the effect of quality characteristics on requirements, the matrix visualizes that the considered technology has an affect or no effect on the downstream process.

The first main step reveals processes (left row), provided by HoQ III, which are necessary for a product. Also, it contains processes that are beyond company boundaries. In addition to the processes, the technologies are gathered for each process (column). The next main step provides information about the influence of a technology on the whole process chain (Fig. 5).

Studies, papers, and information obtained from a firm are used to assess the effect of technology on the downstream processes on a low level of detail. The accumulated information gives an overview of considered technologies and their influence. In contrast to the HoQ, the PTM only visualizes the impact. Thus, essential information must be recorded separately. In this work the symbol ´x´ illustrates connected influence limitation between process and technology and ´1´ illustrates influence of the technology on the process.

The advantage of the PTM after the QFD is that it assesses available technology for individual manufacturing processes. Thus, in the end, there is a decision support to choose the fitting technology to the necessary process that produces the required product components.

Briefly summarized, the conceptual framework consists of two major steps. During the first step, the user develops the multi-step QFD approach. It starts with the analysis of a selected product in the HoQ I and results in the depending, broken down manufacturing processes. Then, the processes are transferred to the PTM, which represents the second step. It contrasts processes with technology (Fig. 3).

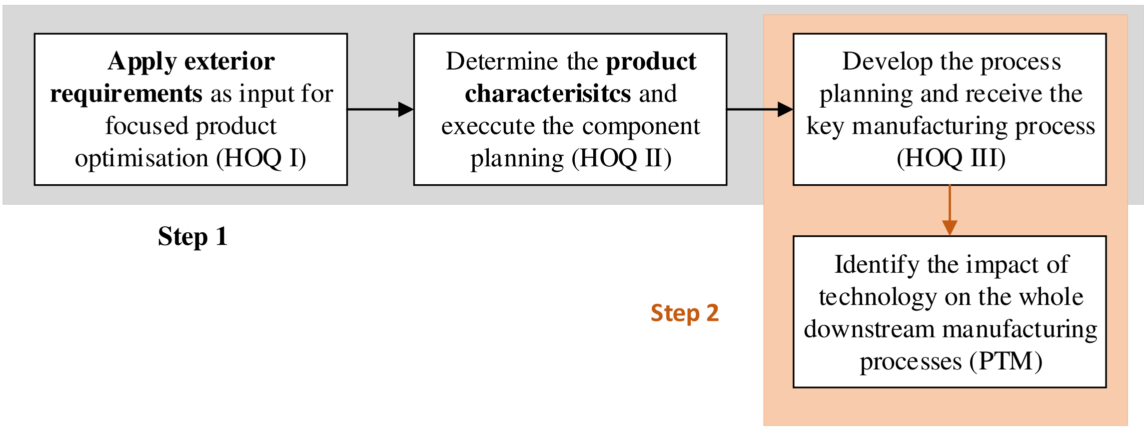


Fig. 3. An overview of the entire methodological process. Step one consists of the execution of the three HoQ. Step two comprises the transition from HoQ III to the PTM and the execution of it.

MATERIAL

In the following section, the SH business is described briefly as well as the three chosen hardwood products solid wood panel, parquet, and glued-laminated timber (GLT). Information and specific data from diverse sources are used to populate the framework. Sources are provided by educated guesses, scientific papers and studies, interviews and discussion with experts, standardizations, wood-based interest magazines, and company brochures. Some references are mentioned within the individual product sections. The multi-step methodology works best when the individual user fills it with their own business data.

Solid Hardwood Supply Chain Designs

Within the SH business sector, there are enterprises that manage the whole supply chain from raw material procurement down to the installation of the end-product; also there are firms specialized on particular added value creating processes (Ouhimmou *et al.* 2008;

Gil and Frayret 2015). Further, there are firms that produce softwood-hardwood-mixed products, too, but they are only specialized in processing and manufacturing of one wood species and procure the other one.

In this study, the secondary industries are considered with sawmills at the beginning and followed by downstream industries (solid wood panel, parquet, and glued laminated timber facility). The manufacturing process steps mainly used in sawmills are log sorting, debarking, scanning, sawing of the log to sawn timber and by-products, timber trimming, timber drying, and grading. These manufacturing steps set up the main processes. Commonly, further manufacturing processes are used to increase the added value and the product variety for the sawmill owner. The manufacturing processes mainly used in the secondary downstream industry are formatting, milling, gluing, finger jointing, assembling, and finishing processes (brushing, colouring, and coatings of wood surfaces).

Almost all manufacturing processes and technologies given in this paper are available and used in the hardwood industry in a certain way or used by companies in part, except continuous drying, which is not applied at all. For producing SH GLT, mainly softwood process and technology configurations are used. At the moment the authors are not aware of any company which continuously produces SH GLT.

Solid Hardwood Resource

Several European countries have a high share of hardwoods in their forest stock (e.g. France, Portugal, Germany, Austria, Poland, Slovakia, Romania); thus the industry of those countries is based on the income from hardwood-based products and the value creation from hardwood products. They are already engaged in comprehensive hardwood research projects (Wehrmann and Torno 2015; Grabner *et al.* 2016; Bollmus *et al.* 2017).

The downstream sector primarily purchases logs from nearby private or public forest owners and delivers hardwood lumber to national or transnational sales markets. The national forest sector is an important supplier of wood for the domestic downstream businesses. The adjacent sawmills and downstream companies are supplied by their regional forestry department.

Selected Solid Hardwood Products

The three selected SH products are presented briefly to give the reader a short overview on the product and the foundation to understand the decisions that are made within the multi-step QFD. SH panels and parquet are traditional, existing hardwood products. In contrast to them, hardwood GLT products are not manufactured continuously up to now.

Solid hardwood panel

SH panels are panel shaped solid wood materials (ÖNORM EN 13353:2011). They consist of finger jointed or continued wood lamellas. These panels are built of one or more wood layers, while every other layer of the multi-layer panels is shifted by 90 degrees. Lamellas used are graded according to firm specific classifications and planed afterwards. The primary use is linked with its characteristics. According to the standard, the final SH panels have a thickness of 20 to 60 mm, a width of max. 1250 mm and a length of max. 15000 mm. SH panels are suited for non-structural products like workbenches, table tops, furniture components or stair cases.

Hardwood parquet

The wood flooring product type parquet is used as one and multi-layer wood flooring product (ÖNORM EN 13756:2018). In both cases, hardwood is used predominantly. In contrast to parquet strips as solid flooring product, the engineered flooring (multi-layer parquet) consists of more than one layer. Each layer has a specific function. One can distinguish between two different functions. The top layer provides the surface that is responsible for abrasion resistance and accounts for the aesthetical appearance. The high degree of hardness of hardwood makes it an appropriate material for parquet flooring. The further layers, which can be also made of softwood species, contribute to the necessary panel thickness and are responsible for dimension stability. There are several parquet types which vary in dimension, composition, installation and appearance (ÖNORM EN 13756:2018).

In this paper, parquet is seen as a multi-layer product. In the following, the focus is put on the production of the parquet lamellas which are produced from pre-manufactured sawn blocks. Currently, the manufacturing process is mainly the sawing process to split-up the pre-sawn and dried timber blocks in order to receive the parquet lamellas for the surface layer. Also, other manufacturing processes such as slicing may be applied.

Hardwood glued laminated timber

In general, GLT is an industrially produced load-bearing engineered wood product, produced from softwoods mainly. It consists of at least two fibre-parallel glued, dried timbers (ÖNORM EN 14080). In the case of hardwood GLT, the hardwood timber planks are graded visually or by machine. Potentially weak points are cut out. Finger joints are used to produce an infinite timber lamella, which is then cut to the requested length. Finally, the length specific timbers are face-glued together fibre-parallel to the required dimension of the beam. Timber for construction is an application area with a high demand on quality assurance and reliability and where well-established companies exist to meet the demand.

Hence, this application area also has moved into the focus of hardwood research. For a decade, increased efforts have been taken to establish several hardwood types in this application field. Comprehensive reviews are provided by Krackler *et al.* (2010, 2011), Blenk *et al.* (2015), as well as Wehrmann and Torno (2015) about hardwood GLT research and utilization. Except for poplar, hardwood GLT is not covered by the EN standard mentioned above. A technical national approval is necessary in order to trade it as a loadbearing building component. At present, several national technical approvals exist to produce hardwood GLT and to apply it in wood or hybrid buildings (Germany: Allgemeine bauaufsichtliche Zulassung Z-9.1-679, Switzerland: SIA 265:2012; SIA 265/1:2009). Hardwood research shows evidence that it is possible to use the hardwood resource for GLT, but it also reveals that the current manufacturing process of GLT is not economically viable (Torno *et al.* 2013).

RESULTS

The following section comprises the results of the multi-step QFD approach as well as the results of the PTM for the three selected SH products. In the context of this paper, it is not possible to present all information from the HoQ tables developed. Therefore, the methodology is extensively executed for the first product. The most important information is highlighted for HOQ and PTM of the other two products.

Solid Hardwood Panel

HoQ I

The initialization of the HoQ I begins with taking down the input parameters in form of requirements. The requirements were directed from the perspective of the customer or the product. Initiatively, the pre-defined requirements were implemented. Then the requirements were weighted on a scale of 1 to 5 (Appendix A - HoQ I). The low importance (2) for cost resulted from the assumption that the costs (procurement, production, delivery) were stable. When considering all requirements, it was more relevant to give greater importance to quality and material utilization (4). Further, dominant quality characteristics, which best met the requirements, were presented in the columns of the HoQ under the HoQ roof. If the developed PQC represents specific requirements, then it can be shown in the RSM. Table 1 provides a brief extract of the requirements, PQC and objectives from the HoQ I.

In order to improve the quality of product, overall requirements were translated into quality characteristics concerning the customer demands. The link between product requirements and PQC is given in the middle part, the RSM. The RSM showed that all requirements were satisfied by one PQC at least (value 9). The requirement of lower product cost was covered by three PQC. A strong link was shown between unit price, product quality and resource utilization to the product cost. The requirement of higher product quality was represented by the PQC dimension tolerance and product quality, lower delivery time by the characteristics through-put time and lead time, higher material yields by the PQC resource utilization, and better design by finishing process. In contrast to the mostly positive influences, there were also influences which limited others. The requirements of higher product quality generated limitations.

Further critical aspects and barriers were taken down in the so-called HoQ roof. The roof gives a quick access of supports or limitations within PQC pairs. High negative correlations existed between unit price and product quality. It was assumed that the production and investment cost were formed due to the increase in product quality. To increase the quality, firms invested in new technology and application to ensure the fulfilment of quality requirements. The roof represented further minor and one higher positive correlation. The latter consisted of two PQC which had to be minimized for a progressive SH panel quality. In this case, it was assumed that the tolerance was a part of the total product quality.

The cellar of the HoQ represents the evaluation part. It consists of PQC objectives and their grading. The objectives of the PQC primarily are in-house definitions. In this case, the SH panel is an interior design product and furniture. It has an optical function. For this purpose, there are standards to be observed but they target at optical quality issues as well as size accuracy and not on mechanical wood characteristics for static issues. From the 11 PQC considered and evaluated, six were chosen because of their results. They were dimension tolerance, through-put time, product quality, resource utilization, dimension geometry, and components connection.

Table 1. Customer Requirements, Product Quality Characteristics and Dependent Objectives for the SH Panel with Examples. Applied in the HoQ I.

What – Customer requirements	How – Product quality characteristics	Objectives
higher product quality	product quality - frequency of errors	frequency of Error after delivery – e. g. 1 %
lower product cost	unit price	41 – 160 €/m³
lower delivery time	through put time	e.g. 7,5 working days
higher material yield	resource recovery	from intermedia product - 85 %
better design	surface quality	firm definition – e.g. roughness after EN ISO 25178

HoQ II

The output of HoQ I became the input of HoQ II, the PQC selected. Further processing was done analogous to the HoQ I. PQC were weighted (Appendix A - HoQ II). The product characteristics of through-put time and resource utilization played an important role in the HoQ II (value 5 and 4). For the PQC, product component characteristics were defined. They are represented in the columns at the top part. The components were divided into sub-sections. Objectives for the sub-sections were taken down in the cellar. For the SH panel, several characteristics are considered which were responsible for the optical function and additive characteristics which were responsible for the connection of the wood parts. The RSM represents the value assignments. Every PQC was satisfied by at least one component characteristic.

HoQ III

In HoQ III, the critical component characteristics formed the requirements for the process characteristics. The first step was to weight the requirements (Appendix A - HoQ III). The material quality was most important for the HoQ III (value 4). Then, the manufacturing process steps were developed and the RSM was edited.

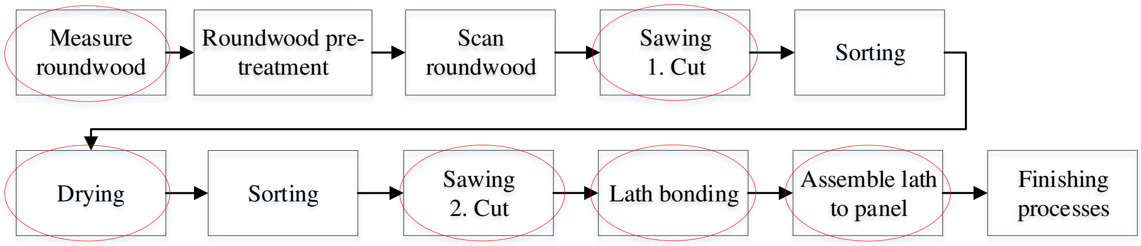


Fig. 4. The process chain for the SH panel is represented. The red cycles are the most important processes if the component requirements from HoQ II are taken into account.

The HoQ III provided the critical processes (

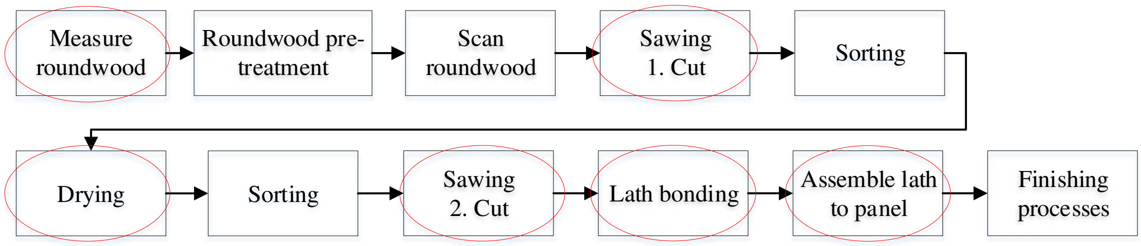


Fig.). The foundation was built from the steps before. Six of 10 were chosen as the most important ones. In the HoQ III evaluation part, the secondary processes such as roundwood scanning or sorting of sawn timber blocks are not as important as the core processes roundwood measurement, cutting, drying, and connecting the components, although the secondary processes play an important role for grading and quality differentiation. These processes are in charge of the selection if the wood piece becomes an expected high value and low value product. Grading rules are used. In the company, a high density of information about the national grading rules is necessary for this step and optimal machine adjustments.

Process-technology matrix

So far, the quality functions of the three HoQ are developed to meet the requirements but little attention has been paid to influences of one process and technology compared to the following downstream manufacturing processes. The PTM concentrates available information and influences that affect upcoming processes (Appendix D). In order to determine the scope of it, all developed process steps were used from the HoQ III. Thus, 11 processes were taken down. The technology section was filled with nine main sections. The first two manufacturing steps were combined to one section, which contained the pre-processing technologies for the roundwood. One process was left out within the technology section, the de-stacking.

A closer look will be taken on drying process (Fig. 5). The drying process was separated into pre-drying, natural drying, and technical drying. Air drying and conventional drying are technologies with the least limitation, the greatest frequency of use, and the highest quantity of research. Their advantages are based on low cost and high quality. In contrast, the other technologies contain limitations in cost and quality, but they have advantages in higher process speed for specific technology-wood type combinations.

In this case, it is to say that the PTM gives only an overview. For example, air drying and conventional drying are just superordinate categories of drying concepts. The several existing implementations of air drying and the machine configurations for conventional drying are not mentioned. The individual user has to carry out the method part according to his or her requirements and data basis to achieve a detailed level to assess technology and processes. With the support of a more extensive data basis for the PTM, the user could not only say that continuous, vacuum and alternative drying concepts and technologies have a limiting effect on the downstream processes and products but also which limitations and how it limits and effects the product quality or downstream processes.

From the given PTM for the SH panel, it can be concluded that air drying as pre-drying and conventional drying as technical drying should be chosen.

	orti	Drying						ak I
		Pre-Dry		Technical Drying				t. +
Technology / Process	Box Sorting	Air Drying	Alternative	Conventional Drying	Continuous Drying	Vacuum Drying	Alternative	Thin-Cutting Band Saw (horizontal)
Roundwood Measurement (Length, Top- and Mid-Diameters)								x
Splinter Detection - Debarking – Cross-Cut								
Scan (visual) for Sawing Centre/Turning								
Sawing	x							x
Sorting (visual criteria) Stacking	x							
Drying		1	x	1	x	x	x	
Stacking - Sorting		1	1	1	1	1	1	
2. Cut (Formatting) Cross-Cut, Trim, Plane		1	x	1	x	x	x	1
Lath Bonding		1	x	1	x	x	x	1
Assemble Lath to Solid Wood Panels		1	x	1	x	x	x	1
Finishing		1	x	1	x	x	x	

Fig. 5. An extract of the SH panel PTM is represented (Appendix D). On the left site, the manufacturing processes are illustrated, which are developed in the HoQ III. The top illustrates the gathered technology to one process. Here, the drying process is represented with its drying technology concepts. The drying process itself has an impact on all downstream processes. Air and conventional drying are the drying concepts with low negative impact on the downstream processes and quality.

Hardwood Parquet

HoQ I, II, III

For the HoQ I, the same requirements were used as for the SH panel. The parquet product characteristic objectives were developed as well as the RSM (Appendix B). Supplementary to the solid panel, wood product humidity, surface quality and dimension stability were an important evidence for the product quality of SH parquet. Analogous to the SH panel production, the same processes were executed from the roundwood manufacturing to the sawing of the parquet bloc. After the second sawing process, the main- and co-products were graded and separated. The parquet blocs were moved to the third sawing process for the parquet lamellas production. These processes were followed by sorting according to the surface quality, top layer production (gluing and pressing), conditioning, joining of the three layers and finally the profiling and finishing processes (Fig. 6).

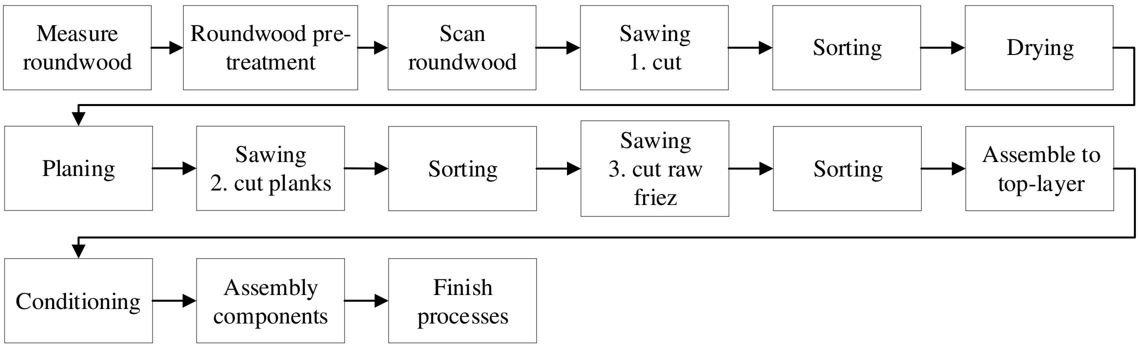


Fig. 6. The general process chain is represented for the solid parquet production.

Process-technology matrix

A total of 15 processes were transferred from the HoQ III to the PTM (Appendix E). The ultimate result showed diverged process flows for the SH parquet production. Three slightly different manufacturing process chains were developed whereby process steps could be reduced. Related technologies were taken down in columns to the required production processes.

For the conventional parquet production, three disintegration processes were necessary from roundwood to parquet lamella. Every disintegration process was followed by a grading step. The grading step grouped the intermedia products. The last steps contained top layer and components assembly as well as finally finishing process.

The standard production line branching-off was caused by an alternative technology, which was inserted into the disintegrating process step, the veneer slicing. Currently, veneer slicing is not a standard process for decorative top layer but implementations were done to slice final parquet lamella to the dimension of 1.5 mm to 4 mm.

The new veneering process replaced the different cutting technologies from the roundwood until the thin-cutting of the lamellas. For each exchange of the technology, the slicing machines had to be adjusted to the appropriate requirements because the input material changed with progressing production. Further, intermedia steps were reduced depending on veneer slicing incorporation between roundwood processing and top layer building (Fig. 7).

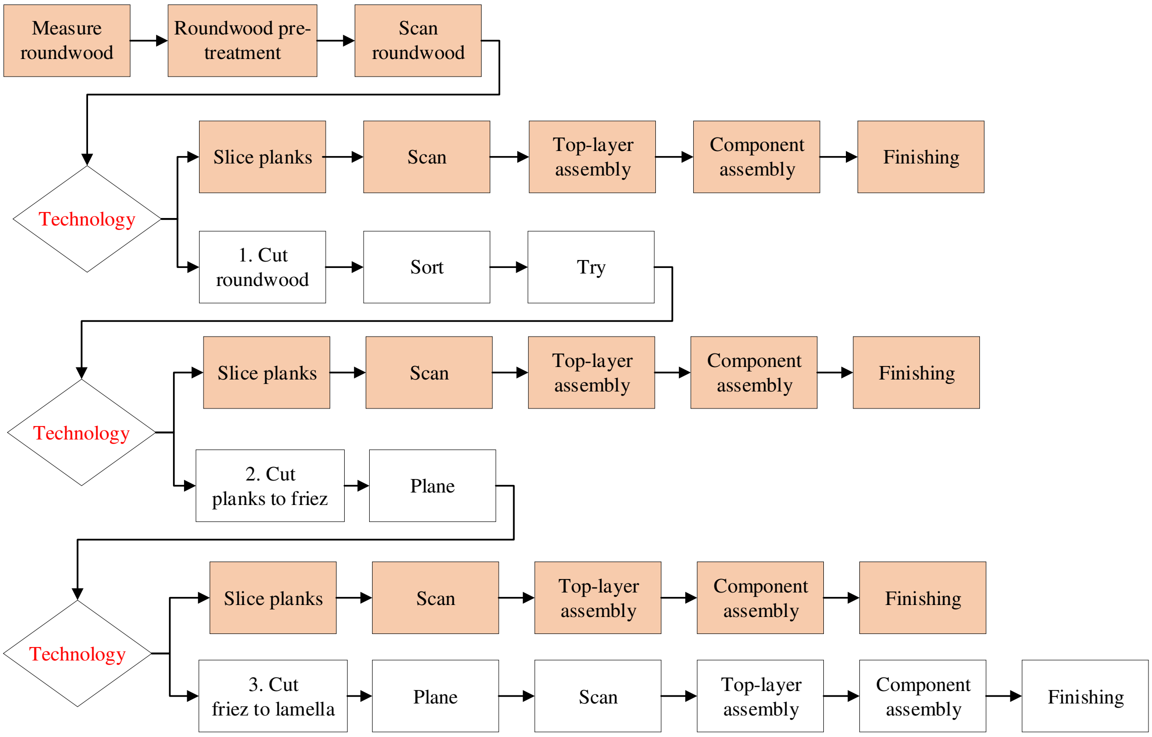


Fig. 7. The divergent process chain is represented for the solid parquet production. It is a result of the general process chain development by QFD in combination with the Process-Technology Matrix. The branching happened at the technology selection. Here, every technology branch represents either a sawing process or a slicing process. The traditional and most used process includes the three break down process. The new manufacturing includes one break down process which is followed by slicing.

Hardwood Glued Laminated Timber

HoQ I, II, III & Process-Technology Matrix

For the hardwood GLT product, the same input requirements were used. Their importance was defined by weightings. High values were assigned to lower product cost (5) and lower delivery time (4) as well as higher material utilization (4) because of low yield material utilization, high unit costs per cubic meter, missing of suitable standard processes, and purchasable product dimensions as well as the related low delivery time for hardwood lamellas, which were identified by scientific research and practical experience.

Dealing with the HoQ I, strength class and standard requirements were added, and product dimension stability was removed (Appendix C). In addition, the optimization directions shifted because of the new objectives associated for the PQC. All requirements are satisfied by at least one PQC (value 9). Further, contra-productive influences were captured for unit cost, surface quality and through-put time on product cost and quality. Here, it is assumed that the higher quality will increase the production cost; therefore the assigned value is negative. The same is assumed for the surface quality. In the case of the stable through-put time, it is assumed that the effort for higher quality influences the production time and is negative to the lower production cost. Most important PQC was the utilization of raw material with a 20% share. In HoQ II, the objectives for the quality component characteristics were taken down under the RSM. The objectives solely based on standardization in the case of the GLT product. The requirements for the material strength of the GLT had to be ensured. After the identification of the main quality component characteristics, the key aspects were transferred to the HoQ III.

For hardwood, missing comprehensive information of the inner stem structure made it necessary to saw stems into untreated, undried wooden planks. The concept based on the fact to obtain lamellas from dried wooden blanks. More information could be gathered from dried planks. Thus, visual quality grading would be possible. Afterwards, the graded planks were ripped into main and co-products with a multi-rip saw. The following steps were equal to the softwood GLT production concept (Fig. 8). Afterwards, the PTM was conducted (Appendix F).

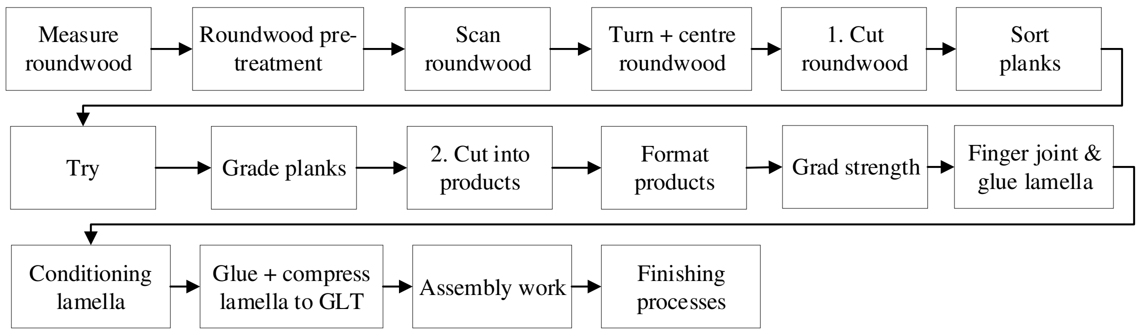


Fig. 8. The general process chain is represented for the hardwood GLT

DISCUSSION

The method developed was designed to analyze systematically the product, process, and technology and to support decisions improving hardwood operations. In the following we will discuss the results generated for the hardwood products under consideration and the framework applied.

To fulfil standardization and national approvals, upcoming hardwood products should have the focus more on the technical data of the components and process parameter to guarantee the quality of the assembled product. Hardwoods have specific properties that can be tackled by fitting technology concepts in order to selectively use them in different application areas. For appearance applications and new construction products, several product components should show optimal performance in dimension, wood moisture content or gluing system. The section objectives of the HoQ determined target values and quality objectives which support the observance of the demanded parameters.

Also, the HoQ correlation matrix in the roof was important. In this work, it was executed only for the HoQ I. To highlight the critical aspects and barriers between the components or between processes it should be executed for the HoQ II and III. This part was considered in a limited extent methodologically due to the data and information available. For a more comprehensive approach to the correlation matrix and possible adaptations, reference is made to further literature such as Melemez *et al.* (2013) or Hauser and Clausing (1988).

Furthermore, results suggest that researchers and practitioner should not draw far-reaching conclusions from exemplary hardwood GLT productions on manufacturing systems which were designed for a different purpose like panel or floor products.

According to Marsillac and Roh (2014), "product architecture changes that are more substantial and complex will generate more substantial and complex changes in the process and supply chain systems associated with them". This can be shown for the three hardwood products and their subordinated application classes. Contrary to the solid panel and parquet product, the hardwood GLT product differed in the application area, number of manufacturing processes and the types of processes which are shown in HoQ III and the PTM. Additionally, the applied GLT technology as well as its complexity level differed (Tani and Cimatti 2008). Also, Marsillac and Roh (2014) notice that production lines are designed to meet manufacturing needs with their specific design characteristics. For the SH industry and the selected products in this work, this means that if the sawmill production lines were designed to meet requirements for appearance applications, they can not achieve an economical production for high technical products for construction applications. For example, if existing sawing patterns are designed to meet the demands of sawn wood for appearance products, they have to be reconsidered for construction products thus the product-process portfolio fits along the supply chain and the individual companies (Torno *et al.* 2013; Abasian *et al.* 2016).

Optimization potential exists within the SH manufacturing chain, although there are standard product types. In the case study, it is based on process and technology shifts. The gathered results for the parquet product suggest that the production chain can be reengineered by the allowance of alternative technology concepts. The process slicing with dependent technology could be integrated rather than sawing. It could reduce the current manufacturing chain by several sawing steps which generated also extensive changes in the manufacturing and supply chain systems which are associated with them.

For the authors of the paper, the utilization of the multi-step procedure was not that challenging, such as collecting of processing information and data. In contrast, for companies it will be the other way round. The first executions of the systemic approach with several steps will need a training period. However, the same procedure in every HoQ with just different information helps to use the method. A workshop will increase the speed to use the method and generate a deeper understanding of the linked information. Within the workshop, a design team will use the multi-step approach to develop their common product from the weighting of requirements over defining PQC to manufacturing processes and technologies.

As mentioned before, collecting information and data for the several HoQ was a challenge. Considering the manufacturing of hardwood GLT, there was an information gap in how to produce hardwood lamellas economically, from saw log down to the beam and which technology should be applied. Less information was found for HoQ III and the PTM.

Every time the multi-step QFD is performed, it starts with determining the requirements. This paper is more focused on developing the HoQ phases and PTM. Thus, the weightings were determined and allocated. These weightings change for each product. In a firm’s context, providing customer requirements will be very challenging but also valuable for the company that has to deal with customer opinions and the market more intensively.

CONCLUSIONS

1. This study evolves a conceptual framework for a methodology to disaggregate SH products to their physical blocks, functions, processes, and dependent technology in order to support the SH business that require redesigning and revisiting of conceptual considerations. The SH products panel, parquet and GLT have been chosen to illustrate the concept.
2. The approach has examined the possibility of integrating product architecture, manufacturing processes and technology solutions into a systematic approach in order to analyze and identify the relations between them and how the relations have affected each other.
3. Based on multi-step Quality Function Deployment and Process-Technology Matrix approach, the developed methodology has visualized how influences of the three

aspects interact. Requirements on products have been represented by the HoQ I. The match of product components and manufacturing processes has been devised with the HoQ II and III. The potential influence of a chosen technology has been demonstrated with the PTM.

4. Manufacturing systems must match the specific product design requirements. These requirements change for easy or complex innovative product as well as for products which have been determined for different application areas – here for appearance or construction applications
5. The contribution of this work is the development of a comprehensive method that provides and visualizes information as well as specific data systematically to support operational decisions and determine better courses of action, whether for managers, practitioners, or researchers. However, the general examples used here are only a sample and so may limit the implications of detailed results. In this work, the ideal manufacturing process chains for three hardwood products have been considered. For significant results, company owners and operation managers of one specific supply chain need to apply the method. Thus, results received can be compared with the original manufacturing chains to identify optimization potential. Also, there has not been a feasibility study or comparison of possible technology for one process. Here, the results point at further potential to integrate other methods, *e.g.* AHP could be used for multi-criterial decisions in the technology selection process.

ACKNOWLEDGMENTS

Financial support for this work in the framework of the PhD-School DokIn´Holz funded by the Austrian Federal Ministry of Science, Research and Economy as well as the Austrian Federal Forestry and the Austrian Chamber of Agriculture is gratefully acknowledged.

REFERENCES CITED

Abasian, F., Rönnqvist, M., and Ouhimmou, M. (2016). "Forest fibre network design with multiple assortments: A case study in Newfoundland," *Canadian Journal of Forest Research* 47, 1232-1243. DOI: 10.1139/cjfr-2016-0504.

Akao, Y. (1990). *Quality Function Deployment: Integrating Customer Requirements into Product Design*, Cambridge, Mass.: Productivity Press. ISBN: 978-0915299416.

Akao, Y., and Chan, C. (2011). "Historical development and the basis of QFD," ISQFD 2011 - 17th International QFD Symposium, 2011.

Allgemeine bauaufsichtliche Zulassung Z-9.1-679. BS-Holz aus Buche und BS-Holz Buche-Hybridträger English: German technical approval Z-9.1-679. "Beech glued laminated timber and beech hybrid beam," Valid 27 October. Deutsches Institut für Bautechnik.

Berendt, F., Fortin, M., Jaeger, D., and Schweier, J. (2017). "How climate change will affect forest composition and forest operations in Baden-Württemberg—A GIS-based case study approach," *Forests 8*, 298. DOI: 10.3390/f8080298.

Blenk, M., Wehrmann, W., and Torno, S. (2015). "Laubholz für tragende Konstruktionen - Zusammenstellung zum Stand von Forschung und Entwicklung"; English: "Hardwood for load-bearing constructions - Compilation on the state of art in research and development."

BMLFUW. (2015). Austrian Forest Report 2015. BMLFUW - Federal Ministry of Agriculture, Forestry, Environment and Water Management. Vienna. Editor: Johannes Prem.

Bollmus, S., Gellerich, A., Schlotzhauer, P., Behr, G., and Militz, H. (2017). "Hardwood research at the Georg-August University of Goettingen," ISCHP 2017: 6th International Scientific Conference on Hardwood Processing: 97-102.

Fine, C. (2000). "Clockspeed-based strategies for supply chain design," *Production and Operations Management* 9(3), 213-221. DOI: 10.1111/j.1937-5956.2000.tb00134.x.

Franceschini, F., Galetto, M., and Turina, E. (2009). "Service quality monitoring by performance indicators: A proposal for a structured methodology," in: *International Journal of Services and Operations Management* 5(2), 251-273. DOI: 10.1504/IJSOM.2009.023235.

Gil, A., and Frayret, J.-M. (2015). "Log classification in the hardwood timber industry: Method and value analysis," *International Journal of Production Research* 54(15), 4669-4688. DOI: 10.1080/00207543.2015.1106607.

Grabner, M., Wolf, A., Schwabl, E., and Schickhofer, G. (2016). "Methods of forming veneer structures," in: *World Conference on Timber Engineering 2016*. ISBN: 9783903024359, 849–858.

Gusakova, A. (2016). *The Competitive Analysis of Selected Biorefineries in Finland*, Master Thesis, Industrial Engineering and Management, Lappeenranta University of Technology. School of Business and Management.

Hauser, J. R., and Clausing, D. (1988). *The House of Quality*, Harvard Business Review.

Hayes, R., and Wheelwright, S. (1979). *Link Manufacturing Process and Product Life Cycles*, Harvard Business Review.

Krackler, V., Keunecke, D., adn Niemz, P. (2010). *Verarbeitung und Verwendungsmöglichkeiten von Laubholz und Laubholzresten*. English: *Processing and Utilization of Hardwood and Hardwood By-Products*. DOI: 10.3929/ethz-a-006113078.

Krackler, V., Keunecker, D., Niemz P., and Hurst, A. (2011). "Possible field of hardwood application," *Wood Research* 2011, 125-136.

Lin, C., and Chang, C.-C. (2015). "The effect of technological diversification on organizational performance: An empirical study of S&P 500 manufacturing firms," *Technological Forecasting and Social Change* 90(Part B), 575-586. DOI: 10.1016/j.techfore.2014.02.014.

Luppold, W., and Baumgardner, M. (2015). "Examination of worldwide hardwood lumber production, trade and apparent consumption: 1995-2013," *Wood and Fiber Science* 47(3), 283-294.

Mai, C. (1998). *Effiziente Produktplanung mit Quality Funktion Deployment*. English: *Efficient Product Planning with Quality Function Deployment*, Springer-Verlag. ISBN: 978-3-642-47913-7.

Marsillac, E., and Roh, J. J. (2014). "Connecting product design, process and supply chain decisions to strengthen global supply chain capabilities," *International Journal of Production Economics* 147, 317-329. DOI: 10.1016/j.ijpe.2013.04.011.

Massa, G., and Gessa N. (2016). "QFD for a SME network of the wood sector to improve competitiveness and sustainability," in: *Sustainable Design and Manufacturing 2016. SDM 2016. Smart Innovation, Systems and Technologies*, R. Setchi, R. Howlett, Y. Liu, P. Theobald (eds.), Vol 52, Springer Nature.

Melemez, K., Di Gironimo, G., Esposito, G., and Lanzotti, A. (2013). "Concept design in virtual reality of a forestry trailer using a QFD-TRIZ based approach," *Turkish Journal of Agriculture and Forestry* 37, 789-801. DOI: 10.3906/tar-1302-29.

Neyses, B., and Sandberg, D. (2015). "A new methodology to select hardwood species for wooden products," *Wood Material Science & Engineering* 10(4), 344-352.
ÖNORM EN 13353 (2011). "Solid wood panels (SWP) – Requirements".
ÖNORM EN 13756 (2018). "Wood flooring and parquet - Terminology".
ÖNORM EN 14080 (2013). "Timber structures - Glued laminated timber and glued solid timber".
Ouhimmou, M., D'Amours, S., Beauregard, R., Ait-Kadi, D., and Chauhan, S. S. (2008). "Furniture supply chain tactical planning optimization using a time decomposition approach," *European Journal of Operational Research* 189(3), 952-970. DOI: 10.1016/j.ejor.2007.01.064.
Saatweber, J. (2011). "Kundenorientierung durch Quality Function Deployment," English: "Customer oriented with quality function deployment," Düsseldorf: Symposion Publishing GmbH. ISBN: 978-3-86329-429-8.
SIA 265/1:2009. "Timber structures – Supplementary specifications," Swiss Society of Engineers and Architects.
SIA 265:2012. "Timber Structures," Swiss Society of Engineers and Architects.
Tani, G., and Cimatti, B. (2008). "Technological complexity: A support to management decisions for product engineering and manufacturing," IEEM 2008 The IEEE International Conference on Industrial Engineering and Engineering Management: 6–11.
Temponi, C., Yen, J., and Tiao, A. (1999). "House of quality: A fuzzy logic-based requirements analysis," *European Journal of Operational Research* 117(2), 340-354. DOI: 10.1016/S0377-2217(98)00275-6.
Thompson, M. K., Stolfi, A., and Mischkot, M. (2016). "Process chain modelling and selection in an additive manufacturing context," *CIRP Journal of Manufacturing Science and Technology* 12, 25-34. DOI: 10.1016/j.cirpj.2015.09.005.
Toivonen, R. M. (2012). "Product quality and value from consumer perspective—An application to wooden products," *Journal of Forest Economics* 18(2), 157-173. DOI: 10.1016/j.jfe.2011.12.004.
Torno, S., Knorz, M., and Jan-Willem van de Kuilen (2013). "Supply of beech lamellas for the production of glued laminated timber," 4th International Scientific Conference on Hardwood Processing. pp. 210-217.
Ulrich, K. T., and Eppinger, S. D. (2015). "Product design and development," Boston. Irwin/McGraw-Hill. ISBN: 978-0073404776.
Wagenführer, A., and Scholz, F. (2018). *Taschenbuch der Holztechnik*. English: *Paperback of Wood Technology*. Hansa. ISBN: 978-3-446-45440-8
Wagner, E., Hansen, E., and Ungson, G. (2007). "Using quality function deployment to assess if a strategy is market-oriented," *J. Forest Products Business Res.* 4(1).
Wehrmann, W., and Torno, S. (2015). *Laubholz für tragende Konstruktionen – Zusammenstellung zum Stand von Forschung und Entwicklung*, English: *Hardwood for Load-bearing Constructions - Compilation to the State of Research and Development*, Cluster Initiative Forst und Holz in Bayern gGmbH, Freising.
Wolfsmayr, U., and Rauch, P. (2014). "Primary forest fuel supply chain: assessing barriers and drivers for the modal shift from truck to train," *Silva Fennica* 48(5). DOI: 10.14214/sf.1217.

Article submitted: April 23, 2018; Peer review completed: November 5, 2018; Revised version received and accepted: January 22, 2019; Published: January 31, 2019.
DOI: 10.15376/biores.14.1.2229-2255

APPENDIX A – HOQ I + II + III – SOLID HARDWOOD PANEL

	1	2	3	4	5	6	7	8	9	10	11
11											
10											
9											
8											
7										+	
6								+			+
5							+				
4					+		+	-			+
3				++	+	+	+	-			+
2											
1				–		-				+	
Product Aspect	Price	Material						Production			Efficiency

QFD HoQ I Solid Hardwood Panel – How: Product Characteristics / What: Requirements	Weighting [1-5]	Relative Share [%]	Quality Product Characteristics	Unit Price	Dimension Geometry - Panel Dimension	Dimension Tolerence - Length, Widh, Depth	Product Quality - Frequency of Errors	Wood Product Humidity - final product humidity	Surface Quality	Dimension Stability	Through-Put Time	Lead Time	Connections of Components	Resource Recovery
Mean Value:	3,00	20%	#	1	2	3	4	5	6	7	8	9	10	11
Sum:	15	100%	Direction of optimisation	-	/	-	-	/	-	+	-	-	/	+
Customer/Firm/Supply Chain														
1 higher product quality	4	27%		-3	3	9	9	3	1	3	1	0	3	0
2 lower product cost	2	13%		9	1	1	9	1	1	1	3	1	3	9
3 lower delivery time	2	13%		1	1	1	1	0	0	0	9	9	0	1
4 higher material yield	4	27%		3	3	1	1	0	0	0	0	0	3	9
5 better design	3	20%		-1	3	3	1	0	3	1	0	0	3	0
			Objectives	41 -160 €/m²	LxWxD =2500x1220x40 [mm³]	+/- 2,0 mm EN 13353	Frequency of Errors (after dilvery) 1 %	9 +/-2 %	Internal Determined Roughness after EN ISO	Amount and Lenght of Cracks	7,5 Working Days	10 Working Days	Glue, Joint (Type, Classification, Time, Cost)	From Intermediate Product 85%
			Importance abs.	17	37	53	63	14	15	17	28	20	39	56
			Importance rel.	4,7%	10,3%	14,8%	17,5%	3,9%	4,2%	4,7%	7,8%	5,6%	10,9%	15,6%
			Sum	359										

HoQ II Solid Hardwood Panel				Material Quality	Grain Direction	Dimension Laths	Lath Tolerance Length, Width	Lath Tolerance Thickness	Application Area	Surface Requirements (Roughness)	Coating Marerial	Connection System	Adhesive Type	Connection Quality	Open Time
			System Class	Wood Part								Auxiliary		Others	
			Sub-Class	Laths - Lamella								Connection System			
			Function	Optic								Connection			
What: Design Requirements From HoQ I / How: Component															
#	**Product Characteristics**	**Objectives**	**Weighting [1-5]**	1	2	3	4	5	6	7	8	9	10	11	12
1	Dimension Geometry - Panel Dimension	LxWxD =2500x1220x40 [mm³]	2	0	0	9	9	1	3	0	0	3	0	0	1
3	Dimension Tolerence - length, widh, depth	+/- 2,0 mm EN 13353	1	1	3	3	9	0	0	0	0	3	0	0	0
4	Product Quality - Frequency of Errors	Frequency of Errors (after dilvery) 5%	3	3	3	9	3	0	0	1	0	3	0	3	3
8	Through-Put Time	7,5 Working Days	5	3	1	3	0	0	0	0	3	9	9	0	1
10	Connections of Components	Glue, Joint (Type, Classification, Time, Cost)	1	1	3	0	1	0	3	0	0	9	3	1	1
11	Resource Recovery	From Intermediate Product 85%	4	9	0	3	0	0	0	3	0	3	1	0	0
			Objectives	ON EN 13489 Multi-Layer Parquet (Page 10)	"standing" - 60°-90°	Depth > 19 mm; Width > 40 mm; Length = depending on type	Firm Setting	Firm Setting	Carpentry, Furniture, Interior Design	Internal Determined Roughness after EN ISO 25178	Oil Type	Connection with Adhesive	Casein Glue -bonding class D-3 according to EN 204	EN 13354 - Mechanical Characterisation	30 min
			Importance abs.	62	20	75	37	2	9	15	15	84	52	10	17
			Importance rel.	15,6%	5,0%	18,8%	9,3%	0,5%	2,3%	3,8%	3,8%	21,1%	13,1%	2,5%	4,3%
			Sum	398											

HoQ III
Solid Hardwood Panel

What
Component CHaracteristics
From HoQ II

How
Process

#	Component Characteristics	Objectives	Weighting [1-5]	Round-wood Measurement (Length, Top- and Mid-Diameters)	Splinter Detection - Debarking – Cross-Cut	Scan (visual) for Sawing Centre/Turning	Sawing - 1. cut	Sorting (visual criteria) Stacking	Drying	Stacking - Sorting	2. Cut (Formatting) Cross-Cut, Trim, Plane	Lath Bonding	Assemble Lath to Solid Wood Panels	Finishing	
			System												
			Group	Lath Manufacturing					Panel Manufacturing						
			Component												
				1	2	3	4	5	6	7		8	9	10	
1	Material Quality	ON EN 13489 Multi-Layer Parquet (Page 10)	4	9	1	3	9	3	9	0	3	1	3	0	
2	Grain Direction	standing - 60°-90°	3	0	0	3	9	0	0	0	6	0	0	0	
3	Dimension Laths	Depth > 19 mm; Width > 40 mm; Length = depending on type	2	9	0	0	9	0	3	0	9	0	0	0	
4	Lath Tolerance Length, Width	Firm Setting	3	0	0	0	3	0	6	0	9	0	0	0	
9	Connection System	Connection with Adhesive	3	0	0	0	1	0	0	0	3	9	9	0	
10	Adhesive Type	Casein Glue -bonding class D-3 according to EN 204	1	0	0	0	0	0	3	0	0	3	3	3	
			Importance abs.	**54**	**4**	**21**	**93**	**12**	**63**	**0**	**84**	**34**	**42**	**3**	410
			Importance rel.	13%	1%	5%	23%	3%	15%	0%	20%	8%	10%	1%	

APPENDIX B – HOQ I + II + III – HARDWOOD PARQUET

Correlation roof (HoQ I)

	1	2	3	4	5	6	7	8	9	10
1			-	--		-			+	
2										
3				++	+	-	+	-		+
4					+		+	-		+
5							+			
6								+		+
7									+	
8										
9										

QFD House of Quality I – Hardwood Parquet (How: Product Characteristics; What: Requirements)

		Weighting [1-5]	Relative Share	Product Aspect	Price	Material						Production		Efficiency
	Quality Characteristics / Product Characteristics				Unit Cost	Product Dimension	Dimension Tolerence - Length, Widh, Depth	Product Quality - Frequency of Errors	Wood Product Humidity - final product humidity	Surface Quality	Dimension Stability	Through-Put Time	Connections of Components	Resource Recovery (Utilisation Yield)
	Mean Value:	3,0	20%	#	1	2	3	4	5	6	7	8	9	10
	Sum:	15	100%	Direction of optimisation	-	/	-	-	/	-	+	-	/	+
Customer/Firm Requirements														
1	Higher product quality	2	13,3%		-3	1	9	9	9	9	9	1	3	1
2	Lower product cost	4	26,7%		9	3	3	3	1	3	3	3	3	9
3	Lower delivery time	4	26,7%		3	9	1	3	1	1	1	9	3	1
4	Higher material yield	3	20,0%		3	3	3	9	3	3	0	1	0	9
5	Better desing	2	13,3%		-3	1	1	3	0	1	1	0	3	3
				Objectives	8 -15 €/m²	LxWxD =1200x120x15 [mm³]	+/- 0,2 mm	Frequency of Errors 0,01 %	7 +/- 2 %	Internal Determined Roughness after EN ISO	Amount and Lenght of Cracks	4 Working Days	Type, Class, Costs	0,75%
				Importance abs.	45	61	45	75	35	45	36	53	36	75
				Importance rel.	8,9%	12,1%	8,9%	14,8%	6,9%	8,9%	7,1%	10,5%	7,1%	14,8%

Importance abs. total: 506

HoQ II – Hardwood Parquet (How: Component; What: Design Requirements)

System Class	Wood Body																	Coating			Others		
Sub-Class	Top Layer									Middle Layer				Bottom Layer				Coating Marerial					
Function	Optic - Hardness - Use-Surface									Transverse Layer				Bearer				Optic - Durability			Joint		Joint
	Thickness of Top-Layer	Material Quality	Surface Quality	Dimension Tolerence - Length, Widh	Curvature Tolerence (longitudinal, transverse)	Application Area	Hardness	Fibre Direction	Cycle Time [Piece/min]	Material Type	Material Quality	Dimension	Provision Time	Material Type	Dimension	Material Quality	Provision Time	Amount of Layers	Surface Requirements Scratching Resistance	Antislip Behaviour	Open Time	Connection Quality	Connection System
# Product Characteristics / Objective / Weighting [1-5]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	22
1 Unit Price / 8-15 €/m² / 3	9	9	3	3	3	1	1	3	1	9	3	0	1	9	0	3	1	1	0	0	0	0	3
2 Product Dimension / LxWxD =2500x1220x40 [mm³] / 3	9	0	0	9	3	3	0	0	0	0	0	9	0	0	9	0	0	1	1	0	0	0	3
4 Product Quality - Frequency of Errors / Frequency of Errors 0,01 % / 5	0	9	1	9	3	3	1	9	0	3	9	0	0	3	0	9	0	1	3	3	3	9	3
8 Through-Put Time / 4 Working Days / 4	3	3	9	1	1	0	0	3	9	3	3	3	3	3	3	3	3	9	0	0	1	0	3
10 Resource Utilisation / 0,75% / 4	3	3	1	0	0	0	0	-1	0	1	3	3	0	1	3	3	0	0	0	0	0	0	3
Objectives	>= 2,5 mm (3-4-mm)	ON EN 13489 Multi-Layer Parquet (Page 10) High	Mean Roughness Index 25-1,6 µm	+/- 0,2 mm	ON EN 13489 Multi-Layer Parquet (Page 11)	Technical Class EN636	EN ISO 6506 (Brinell Hardness Test)	"standing" - "lying" - 0°-90°	12/min	Spruce	Low	Thickness 1,3 mm	60 min within the facility	Oak	Rustic	Middle	30 min within facility	6	1,2 N	Pendulum Test EN 1339	90 min	Mechanical Evaluation (Tension-Shear Test; Time-Walk Test)	Click System (Milling)
Importance abs.	78	96	54	85	37	27	8	62	39	58	78	51	15	58	51	78	15	47	18	15	19	45	57
Importance rel.	7,1%	8,8%	4,9%	7,8%	3,4%	2,5%	0,7%	5,7%	3,6%	5,3%	7,1%	4,7%	1,4%	5,3%	4,7%	7,1%	1,4%	4,3%	1,6%	1,4%	1,7%	4,1%	5,2%

Importance abs. total: 1091

HoQ III – Hardwood Parquet (How: Process; What: Component Characteristics From HoQ II)

#	Component Characteristics	Objective	Weighting [1-5]	Sawlog Measurement - length, top- and mid-diameter	Sawlog Pre-Processing	Scan for Sawing (visual) | Centre/Turning	1. Sawing - Disintegration Sawlog	Sorting for Quality Stapelung	Drying	Planing - Plain Surface	2. Sawing - Disintegration of Planks (Raw Frieze, By-Products, trim)	Sorting	3. Sawing - Raw Frieze to Lamella	Sorting (visual criteria)	Assembly Top-Layer (glueing, pressing)	Conditioning	Assembly Components (glueing, pressing)	Formatting and Finishing
			Part	Roundwood				Timber				Parquet Bloc		Parquet Lamella			Joining	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Thickness of Top-Layer	>= 2,5 mm (3-4-mm)	2	1	1	1	3	3	9	1	3	3	9	0	9	9	3	9
2	Material Quality	ON EN 13489 Multi-Layer Parquet (p. 10)	5	9	1	1	3	3	9	0	1	3	9	3	0	0	1	9
4	Dimension Quality - lenght, width	+/- 0,2 mm	4	3	0	1	6	3	6	6	6	3	6	3	3	6	3	1
8	Fibre Direction	"standing" - "lying" 0° - 90°	4	0	0	9	9	9	3	0	6	3	3	0	0	0	0	0
11	Material Quality (Middle)	Low	1	0	0	0	0	0	0	0	0	0	0	0	0	0	9	6
16	Material Quality (Bottom)	Middle	3	0	0	0	0	0	0	0	0	0	0	0	0	0	9	6
			Importance abs.	59	7	47	81	69	99	26	59	45	99	27	30	42	59	91
			Importance rel.	7%	1%	6%	10%	8%	12%	3%	7%	5%	12%	3%	4%	5%	7%	11%

Importance abs. total: 840

APPENDIX C – HOQ I + II + III – HARDWOOD GLUED-LAMINATED TIMBER

#	1	2	3	4	5	6	7	8	9	10	11
1			-		- -		-	-	+		+
2											
3					++	+	-	-	+	+	+
4											+
5						+		-		+	+
6									+		
7										+	
8											
9										++	
10											
11											

QFD
House of Quality I
Glue Laminated Timber
How
Product
What
Requirements

		Weighting [1-5]	Relative Share [%]	Product Aspect	Price	Material						Production		Efficiency	
				Quality Characteristics Product Characteristics	Unit Cost	Dimension Geometry - GL-Beam	Dimension Tolerence - length, width, depth	Strength Class	Product Quality - Frequency of Errors (post-processing, scrap quantity)	Wood Product Humidity - final application area humidity	Surface Quality (see objective)	Through-Put Time - process time	Connections of Components - quantity	Resource Utilisation (Input Material)	Pass Standard Requirements
	Mean Value:	3,20	20,00%	#	1	2	3	4	5	6	7	8	9	10	11
	Sum:	16	100,00%	Optimisation Direction	-	/	-	+	-	/	/	-	-	+	/
Customer/Firm Requirements															
1	Higher product quality	2	12,50%		-3	3	-1	3	9	3	9	-3	0	0	9
2	Lower product cost	5	31,25%		3	1	1	3	3	0	-3	-3	3	9	0
3	Lower delivery time	4	25,00%		-1	-1	0	0	3	0	-1	9	1	3	1
4	Higher material yield	4	25,00%		9	3	0	0	0	0	0	0	0	0	0
5	Better desing	1	6,25%		1	3	0	0	1	3	9	0	3	0	3
				Objectives	700 € / m³	Width max. 160mm | Heigth max. 600 mm	Size Accurance according to EN 390 - Width: +/- 2 mm | Hight: + 1 %/- 0,5 % | Lenght +/- 0,1 %	> 28 GL	< 1 %	according to area of application / service classes EN 1995-1-1 (1 ~5-15 % - 2~ 10-20 %)	application area - visible or concealed (knot frequency)	40 working days	Delamination EN 14080:2013	From trunk until final main product and co-product >50%	e.g. general type approval or on case-by-case basis
				Importance abs.	42	22	3	21	46	9	8	15	22	57	25
				Importance rel.	15,6%	8,1%	1,1%	7,8%	17,0%	3,3%	3,0%	5,6%	8,1%	21,1%	9,3%

Sum 270

HoQ II
Glue Laminated Timber
How
Component
Characteristics
What
Design Requirements
From HoQ I

			System Class	Wood Body									Auxiliary Materials
			Sub-Class	Lamella									Glue
			Function	Strengh - Weight Distribution									Connection
				Stem Quality	Lamella Dimension Hight	Lamella Dimension Width	Visual Strenght Grading	Machine Strength Grading	Surface Quality	Deviation	Humidity Application Area	Finger Joints	Glue Type I (EN 301)
#	Product Characteristics	Objective	Weighting [1-5]	1	2	3	4	5	6	7	8	9	10
1	Unit Cost	700 € / m³	5	3	3	1	1	1	0	0	1	3	3
2	Dimension Geometry - GL-Beam	Width max. 160mm | Heigth max. 600 mm	2	3	3	3	0	0	0	9	0	1	0
4	Strength Class	> 28 GL	3	1	3	3	9	9	3	1	1	3	0
5	Product Quality - Frequency of Errors	< 1 %	4	1	0	0	3	3	9	1	3	3	3
9	Connections of Components - quantity	Delamination EN 14080:2013	2	3	9	0	0	0	3	3	1	1	3
10	Resource Utilisation (Input Material)	From trunk until final main product and co-product >50%	4	3	3	3	3	3	0	0	0	3	1
11	Pass Standard Requirements	e.g. general type approval or on case-by-case basis	1	0	3	3	1	1	3	3	1	3	3
			Objectives	EN 1316-1 | Grade Sorting (HKS) |Framework agreement for the timber trade in Germany (RVR)	12 mm > x < 30 mm	80 mm > x < 160 mm	DIN 4074-5	According to EN 385 + DIN 4074-5 (E-dyn > 13000 N/mm²)	General Type Approval Z-9.1-679 (plane max. 6 h earlier)	EN 390 - Width: +/- 2 mm | Hight: + 1 %/- 0,5 % | Lenght +/- 0,1 %	9-12 %	DIN EN 140807	Pass Delamination Assay (sufficient waiting time between application and compression)
			Importance abs.	46	63	35	57	57	54	34	23	55	40
			Importance rel.	9,9%	13,6%	7,5%	12,3%	12,3%	11,6%	7,3%	5,0%	11,9%	8,6%

Sum 464

HoQ III Glue Laminated Timber			Part	Roundwood				Timber						Joining				
What Component Characteristics From HoQ II			How Process	Sawlog Measurement - length, top- and mid-diameter	Sawlog Pre-Processing	Scan for Sawing (visual) | Centre/Turning	1. Sawing - Disintegration Sawlog	Sorting for Quality	Drying	Planeing - Plain Surface	Sorting for Strength	2. Sawing - Disintegration of Planks	Formatting (plane, cross-cut)	Produce Infinite Lamella - Finger Joint	Conditioning	Assemble Lamella (glueing, press)	Joinery + Finishing	
#	Component Characteristics	Objective	Weighting [1-5]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1	Stem Quality	EN 1316-1 | HKS | RVR	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	
2	Lamella Dimension Hight	12 mm > x < 30 mm	3	9	0	1	9	1	0	0	0	0	0	0	0	0	0	
4	Visual Strenght Grading	DIN 4074-5	2	0	0	3	0	6	0	0	9	0	0	0	0	0	0	
5	Machine Strength Grading	According to EN 385 + DIN 4074-5 (E-dyn > 13000 N/mm²)	2	0	0	0	0	6	3	0	9	0	0	0	0	0	0	
6	Surface Quality	General Type Approval Z-9.1-679 (plane max. 6 h earlier)	3	0	0	0	9	3	3	9	0	3	3	0	0	0	0	
9	Finger Joints	DIN EN 140807	4	0	0	0	3	0	0	0	0	0	3	9	0	0	0	Sum
			Importance abs.	27	0	12	66	36	15	27	36	9	21	36	0	0	0	285
			Importance rel.	9%	0%	4%	23%	13%	5%	9%	13%	3%	7%	13%	0%	0%	0%	

APPENDIX D – PTM – SOLID HARDWOOD PANEL

Process-Technology Matrix

Solid Hardwood Panel

Technology → / Process ↓	Roundwood Pre-Process		Scanning			1. Break Down							Sorting		Drying						2. Break Down					Glueing							Pressing		Finishing		
						Frame									Pre-Dry		Techn. Drying				Disint. + Trim				Plane								Conti	Batch			
	Splinter Detector	Butt-End Reducer	Colour Scanner	3D Scanner	2D-X-Ray / 3D-X-Ray Computer Tomograph	Frame Saw (vertical)	Frame Saw (vertical)	Chipper Canters Technology	Short Wood Profil Sawing	Reducing Bandsaw Technology	Circular Saw	Band Saw	Manual	Automated Sorting	Air Drying	Alternative	Conventional Drying	Continuous Drying	Vacuum Drying	Alternative	Thin-Cutting Band Saw (horizontal)	Thin-Cutting Frame Saw	Multi-Blade Circular Saw	Automated Cross-Cut Saw (Circular)	Plane or Milling	Manual	Automated	Spray	Roll	Pour	Brush	Others	Continuous	Discontinuous (Multi-Stage Press)	Modification (Steaming, Thermo Wood,...)	Processing (Sand, Plane, Mill)	Coating (Varnish, Oil, Veneer, Colour)
Roundwood Measurement (Length, Top- and Mid-Diameters)		1	1	1	x				x												x	x	x														
Splinter Detection - Debarking – Cross-Cut	1	1																																			
Scan (visual) for Sawing Centre/Turning		1	x	1	x	1	1	1	1	1	1	1		1																							
Sawing				1	x	x	1	1	x	1	x	x									x	x	x														
Sorting (visual criteria) Stacking					x	x	1	1	1	1	1	1	1	1																							
Drying						1	1	1	1	1	1	1		1	1	x	1	x	x	x															1		
Stacking - Sorting															1	1	1	1	1	1																	
2. Cut (Formatting) Cross-Cut, Trim, Plane					x			x							1	x	1	x	x	x	1	1	1	1	1								1	1			1
Lath Bonding															1	x	1	x	x	x	1	1	1	1	1		1	1	1	1	1	1		1			1
Assemble Lath to Solid Wood Panels															1	x	1	x	x	x	1	1	1	1	1		1	1	1	1	1	1		1			1
Finishing					x										1	x	1	x	x	x					1	1	1	1	1	1	1	1	1	1	1	1	1

APPENDIX E – PTM – HARDWOOD PARQUET

Process-Technology Matrix
Hardwood Parquet

Technology → / Process ↓	Scan			1. Break Down								Sorting				Drying						P	C	2. Break Down				Sort		3. Break Down				Sort	Top-Layer Glue	Top-Layer Pressing		Condition		Assemble Glue	Assemble Pressing		Finishing		
																Pre-Dry		Techn.						Disint.+Trim			Alter.	Tec		Standard			Alter.	Tec		Conti	Batch				Conti	Batch			
	Colour Scanner	3D Scanner	2D-X-Ray / 3D-X-Ray Computer	Frame Saw (vertical)	Frame Saw (vertical)	Short Wood Profil Sawing	Chipper Canters Technology	Reducing Bandsaw Technology	Circular Saw	Band Saw	Slicing	Manual	Automated Sorting	Level Sorting	Box Sorting	Air Drying	Alternative	Conventional Drying	Continuous Drying	Vacuum Drying	Alternative	Plane	Automated Cross-Cut Saw	Thin-Cutting Band Saw (horizontal)	Thin-Cutting Frame Saw	Multi-Blade Circular Saw	Slicing	Colour Scanner	3D Outline Scanner	Thin-Cutting Band Saw (horizontal)	Thin-Cutting Frame Saw	Multi-Blade Circular Saw	Slicing	Colour Scanner	Automated	Continuous	Discontinuous (Multi-Stage Press)	Store	Climate Chamber	Automated	Continuous	Discontinuous (Multi-Stage Press)	Modification (Steaming, Thermo Wood,...)	Processing (Sand, Plane, Mill)	Coating (Varnish, Oil, Veneer, Colour)
Roundwood Measurement (Length, Top- and Mid-Diameters)	1	1	x			x			x		x													x	x	x																			
Pre-Processing (Debarking, Cross-Cut,ect)						1	1	1																																					
Scan (visual) for Sawing Centre/Turning		1	x			1	1	1	1	1	1		1																																
1. Sawing -Disintegration Roundwood		1	x	x		x	1		1	x	1			x	x									x	x	x																			
Sorting (visual criteria) Stacking	1		x	x	1	1	1	1	1	1	1	1	1	x	x																														
Drying											1		1			1	x	1	x	x	x																								
Planeing - Plain Surface											1											1	1																						
2. Sawing - Disintegration of plank (Raw Frieze + By-Products; trim)	1		x	1							1						x	1	x	x	x	1		1	1	1	1																		
Sorting											1					1	1	1	1	1	1			1	1	1	1	1	1																
3. Sawing - Raw Frieze to Lamella			x								1					1	x	1	x	x	x	1		1	x	1	1		1	1	1	1	1												
Sorting (visual criteria)											1					1	1	1	1	1	1						1		1	1	1	1	1	1											
Assembly Top-Layer (glueing, pressing)											1					1	x	1	x	x	x						1	1	1	1	1	1	1	1	1	1	1								
Conditioning											1					x	x	x	x	x	x						1						1		1	1	1	1	1						
Assembly Components (glueing, pressing)											1					x	x	x	x	x	x						1						1		1	1	1	1	1	1	1	1			
Formatting and Finishing											1																1						1		1	1	1	1	1	1	1	1	1	1	1

APPENDIX F – PTM – HARDWOOD GLUED-LAMINATED TIMBER

Process-Technology Matrix
Glued-Laminated Timber

	Scanning				1. Break Down							Sorting					Drying						Sorting (Strength) Visual			Sorting (Strength) Machine				2. Break Down	Format		Finger Joint				Assemble Glue	Assemble Pressing		Finishing		
			X-Ray		Frame							Man	Techn.				Pre		Tec				Man	Machine				X-Ray		Disint.+Trim	P	C	Tenon	Glue	Press			Cont	Batch			
Technology → Process	Colour Scanner	3D Scanner	2D	3D CT Scan	Frame Saw (vertical)	Frame Saw (vertical)	Short Wood Profil Sawing	Chipper Canters Technology	Reducing Bandsaw Technology	Circular Saw	Band Saw	Manual	Automated Sorting	Stacking	Level Sorting	Box Sorting	Air Drying	Alternative	Conventional Drying	Continuous Drying	Vacuum Drying	Alternative	Manual	Colour Scanner	3D Laser Outline Scanner	Machine Stressed	Transverse Vibration Technology	2D	3D CT Scan	Multi-Blade Circular Saw	Plane	Automated Cross-Cut Saw	Parquet Finger Joint	Parquet Glueing	Cycle Press	Store	Automated	Continuous	Discontinuous (Multi-Stage Press)	Plane and Mill	Joinery	Coating
Sawlog Measurement (Length, Top- and Mid-Diameters)	1	1	1	x			x			x																																
Pre-Processing (Splinter Detection, Debarking, Cross-Cut)							1	1	1																																	
Scan (visual) for Sawing Centre/Turning		1	1	x			1	1	1	1	1		1																													
1. Sawing -Disintegration Roundwood		1	1	x	x		x	1		1	x			x	x	x																										
Sorting (Quality)	1		1	x	x	1	1	1	1	1	1	1	1	x	x	x																										
Drying																	1	1	1	x	x	x																				
Planeing - Plain Surface				x													1	1	1	1	1	1	1			1	1	x	x													
Sorting (Strength)																																										
2. Sawing - Disintegration of Plank				x								1	1				1	x	1	x	x	x	1	x	x	1	1	x	x	1												
Formatting (plane, cross-cut)																															1	1										
Produce Infinite Lamella - Finger Joint				x													1	x	1	x	x	x	1		1			x	x	1	1		1	1	1							
Conditioning																																				1						
Assemble Lamella (glueing, press)																	x	x	x	x	x	x									1					1	1	1	1			
Joinery + Finishing																																					1	1	1	1	1	1

Paper III

Kühle, S; Teischinger, A; Gronalt, M (2019b): Optimal location of laminated beech production plants within the solid hardwood supply network in Austria. Silva Fennica vol. 53 no. 3 article id10074. 22 p. DOI: 10.14214/sf.10074.

Silva Fennica vol. 53 no. 3 article id 10074
Category: research article
https://doi.org/10.14214/sf.10074

SILVA FENNICA

http://www.silvafennica.fi

ISSN-L 0037-5330 | ISSN 2242-4075 (Online)
The Finnish Society of Forest Science

Sebastian Kühle[1], Alfred Teischinger[1] and Manfred Gronalt[2]

Optimal location of laminated beech production plants within the solid hardwood supply network in Austria

Kühle S., Teischinger A., Gronalt M. (2019). Optimal location of laminated beech production plants within the solid hardwood supply network in Austria. Silva Fennica vol. 53 no. 3 article id 10074. 22 p. https://doi.org/10.14214/sf.10074

Highlights

- This paper provides data to the solid hardwood business and develops a mixed integer linear program model to design a laminated beech wood supply network.
- It covers the strategic decision where to locate a new production facility within the existing supply network with the lowest supply network cost.
- Sufficient sawn wood suppliers and potential facility locations are provided.

Abstract

Due to changes in forest management in various European countries, hardwood forest areas and amounts will increase. Sustainable and individual utilization concepts have to be developed for the upcoming available resource. Studies conclude that there is low potential for hardwoods in the traditional appearance market thus the application areas have to be extended to new structural innovative products. This paper examines the extension to a future laminated beech wood supply network which would be a combination of already existing and new production facilities. For a better future use of hardwood raw materials it is necessary to consider the entire supply chain. This also better shows a total hardwood value chain. Therefore, this paper provides data to the solid hardwood business and develops a mixed integer linear programming to design a laminated beech wood supply network. The model is applied to Austria as the sample region. It covers the important strategic decisions where to locate a downstream facility within the existing production network with the lowest supply network cost. Fourteen scenarios are developed to examine various future network configurations. Results about optimal material flows and used sawmills as well as downstream production facilities are presented in form of material and financial performances. Two optimal laminated beech production locations are determined by the calculated scenarios results, and the impact of a new sawmill is analyzed which is focused on beech.

Keywords decision support system; facility location; laminated timber products; mixed integer linear programming; supply chain network design
Addresses [1]BOKU - University of Natural Resources and Life Sciences, Vienna, Department of Material Science and Process Engineering, and Renewable Institute of Wood Technology Materials, Konrad-Lorenz-Straße 24, 3430 Tulln, Austria; [2]BOKU - University of Natural Resources and Life Sciences, Vienna, Department of Economics and Social Sciences, Institute of Production and Logistics, Feistmantelstraße 4, 1180 Vienna, Austria
E-mail skuehle@boku.ac.at
Received 13 November 2018 Revised 20 June 2019 Accepted 5 July 2019

1 Introduction

1.1 Change of hardwood resources

Currently, within the hardwood business, the challenge is to develop sustainable and individual utilization concepts which consider species, quality, supply network and further aspects because more resource potential will be available prospectively. It becomes apparent that the proportion of deciduous forest area increases as well as the amount of harvested hardwood (BMLFUW 2015a; BMLFUW 2015b; BMEL 2017). The utilization of hardwoods as timber has decreased tremendously in the last two decades in Europe, but the utilization of hardwoods as industrial roundwood and fuel wood develops progressively in contrast.

1.2 Hardwood products

For the hardwood companies, a study by Lehner et al. (2014) concludes that there is low potential to increase the market volume in the traditional area like doors, staircases, flooring and more. The authors see more market potential in the development of glued cross sections based on hardwood or hybrid products for the construction market like hardwood cross-laminated timber, glulam and laminated veneer lumber. For construction applications, the production of lamellas requires defined strength properties by respective standards. Torno et al. (2013) applied such rules on the conversion of beech roundwood leading to the production of lamellas for beech glued laminated timber. They considered saw logs of different dimensions and qualities and three sawing technologies. They analysed the kiln-drying, planing, and strength grading processes. As a result, the yield was found to be between 17% and 22%. One has to highlight that they did not take in account co- and by-products.

In contrast to the technology concepts to produce these hardwood load-bearing component (Krackler et al. 2011; Blenk et al. 2015; Tran et al. 2016; Espinoza and Buehlmann 2018), one of the most important points that has not been addressed so far, is that there is currently no provider on the market who can continuously deliver glued hardwood timber products in Europe. There are less knowledge and experience with modern hardwood supply networks and the performance of structural hardwood applications. Also, comprehensive data about the supply network, stakeholders and the linked material flows is missing.

In addition to the technological requirements for manufacturing as well as strength testing of the lamellas and the depend on production line at the sawmills and downstream facilities, the hardwood supply network also has to be studied about possible quantities of the final products. A coniferous glued-laminated timber (glulam) plant is in the range up to 100 000 m^3 as well as a cross-laminated timber plant. The timber supply for this production capacity must be provided continuously and promptly for further processing along a hardwood supply network. Beech wood is a potential resource for this case but has some availability limitation in summer (Berendt et al. 2017). In Central Europe, it is widespread, and it can be provided for a one-hardwood-type-only product.

1.3 Hardwood supply network

A potential beech wood supply network for laminated beech (LBWSN) would be a combination of already existing stakeholders (forest departments and sawmills) and new stakeholders (laminated wood production facility and customers). In a graph, it is represented by nodes as the stakeholders and arcs as material flow between the nodes thus the material is transported from source nodes, the forest department, over facility nodes to demand zone nodes, which represent the customers.

The main raw material of the supply network is hardwood saw logs. In sawmills, these logs are processed into lamellas using specific cutting patterns for producing rough glulam laminations (Torno et al. 2013). The kiln-dried beech timber is shipped to the downstream facility where it is further manufactured and assembled to various glued hardwood products like glulam or cross-laminated timber. Finally, the products are shipped from the facility to the customer zones.

While the locations and current products are known for forest departments and hardwood sawmills, further data is rather unknown for strategic network planning such as potential production capacities or transformation yield from hardwood roundwood to lamellas. Also, the downstream facilities contain uncertain factors. Production data and economical expense are not available or can be assumed for the downstream facility and the customers. Such data and parameters may comprise facility production capacity, production costs, the potential product demand etc.

In order to reengineer the network and to add new facilities for the downstream, new potential networks have to be designed. These alternatives can include possible suppliers, locations, production and storage capacities as well as marketing and shipment options (Klibi et al. 2010). Within the forest- and wood-based business, the opening up of new facilities are strategic decisions with long-term impact. Thus, it is also important to redesign the capacities and technologies of facilities within the divergent transformation business (Vila et al. 2006).

The collective consideration of individual production units within a supply chain can help to achieve aggregated capacities and resources to satisfy a downstream demand which is impossible as a solitary company. The combination of all these factors makes the planning of the LBWSN complex in the combination of the various factors and difficult in the computation with a big amount of data. The network needs a decision support system to support the strategical planning process and policy makers in the estimation of the potential consequences of their strategic business choices (Drucker 1995).

1.4 Optimization and facility location problem (FLP)

Within the operational research, the supply network design problem (SNDP) restructures supply networks to achieve value creation in stakeholders involved (Klibi et al. 2010).

FLP is a subset of supply network design or discrete problems which deal with the location of at least one facility in a given surrounding. The aim is to optimize the objective function like revenue, profit, cost, distances, covering or others. FLP is applied in public, private or military sector on a national or international level (Farahani et al. 2010). They can be focused on single echelon, single period and capacitated facilities such as manufacturing or distribution facility location-allocation problems. Facilities locations are chosen from a determined set of candidates to satisfy the demand of customers. The objective is to minimize the total cost covering fixed opening and variable operational cost or transport cost (ReVelle et al. 2008).

Furthermore, Melo et al. (2009) identified four elementary aspects in their review which may be considered in strategic supply chain planning with FLP: multi-layer/multi-capacity facilities, multi commodities, single/multiple periods, as well as deterministic or stochastic parameters. For example, the benefit of using multiple periods is that supply network designs can be adapted to parameters which change over the periods like resource availability or customer demand.

Within the forest- and wood-based sector, a high share of FLP publications deals with the use of woody biomass for heat and energy generation or as a resource for biorefineries. The contribution is the allocation of resource amounts and locations to plants or to biorefinery facilities as well as the opening of intermediate storage locations for the transport from source to the user (Gronalt and Rauch 2007; Rauch and Gronalt 2010; Kanzian et al. 2013; Johnson et al. 2014). Advanced FLP focus on integrated facilities within a supply chain network. Integrated biorefinery and forest product supply chain network designs are studied to support organizations in their investment decision (Feng et al. 2010; Abasian et al. 2017). Further, FLP can consider biorefineries technologies which can lead to centralized or decentralized plant concepts (Walther et al. 2012).

These integrated forest supply chain models represent almost unreachable, ideal networks. They consist of a cooperative and connective supply chain with optimal material and information flows. However, the real world problems have stakeholders with their own objectives thus lacks of coordination occur between stakeholders. Therefore, Alayet et al. (2018) provide a forest supply network model with independent business unites which are linked through interdependent processes. The model helps to study applied supply chain management methods. In their work, they compare Make-to-Order, Vendor Managed Inventory, and a centralized planning approach. The latter leads to the highest profit. The network design is characterized by perfect collaboration. The Vendor Managed Inventory approach fits for a business environment which is more characterized by competition and non-collaborative.

Klibi et al. (2010) mentioned that there are three major classes of value drivers which should be taken into account in supply chain network design. They are revenue drivers, cost drivers and capital expenditure. All three are not necessarily relevant for supply network design at the same time. If models use deterministic demand for the given number of periods, the revenues can be seen as a constant and the model objective just minimizes the supply network cost. Further, a review of facility location SCM shows that three fourth of the considered literature applied cost minimization objectives. That is highlighted by the authors because most businesses are profit oriented (Melo et al. 2009).

Finally, there is uncertainty involved in strategic planning processes with high investments. This means that there is not sufficient information at a specific time to predict specific resource, demand, sales or other developments in the future. One method to tackle uncertainty is the development of appropriate scenarios representing potential alternative futures that can be analyzed (Mansoornejad 2012).

For the laminated beech wood production network, there is no optimization model with collected data which could support the opening of downstream facilities to produce the laminated products yet available.

The presented works deal with supply network design, i.e. location problems in the forest- and wood-based business and hardwood products. None of the basic works relates in particular to the hardwood sector, which has an increased potential for raw material growth due to the emerging climate change. The novelty in this paper is the application of the existing models to the solid hardwood sector. Therefore, the main contribution of the paper is to collect data about the solid hardwood business for developing a strategic planning model to design a supply network for laminated beech products. Therefore, this research focuses on the FLP within a supply network design with the following characteristics:

- The laminated beech wood supply network under consideration is a multi-period, single-product and multi-layer supply network.
- Demand in each period (monthly) is deterministic and known.
- At least one facility is opened from a set of candidates.
- Customers can receive the product from one or multiple downstream facilities.
- Several different possible scenarios are used to simulate various network designs.

The results support decision makers where to locate a downstream facility within an existing production network with the lowest supply network cost and which hardwood sawmills should be involved in the upcoming implementation phase.

This paper aims to support standard decisions within the solid hardwood network where to allocate new manufacturing facilities for load-bearing applications and to analyses the beech material flow within the hardwood supply network for laminated timber purposes.

2 Material and methods

The following section describes the considered supply chain and its entities with forest departments, sawmills, downstream facilities and customers (Fig. 1). Data will be provided for each considered entity. It is from several sources as well as calculated and determined. Then, the mathematical program model description will present the exact formulation. It is followed by the chosen scenario. They are edited based on various roundwood supply and production capacity configurations to demonstrate the impact on the network design and because of the uncertainty of future developments. The section is completed with data preparation and processing.

2.1 Supply network

2.1.1 Forest areas, distribution and roundwood supply

48% of Austria were covered with forests in 2013. The annual increment was 30.4 million m^3 of standing wood and 25.9 million m^3 (85%) of it was harvested. 82% of the forest land is owned by the private and 18% by the public sector. The forest area consists of 28 % deciduous and 72% coniferous tree shares (proHolz 2013). In the case of wood harvesting, the proportion was 83% softwood and 17% hardwood in 2015. All in all, 17.5 million m^3 of the harvested wood was utilized, as there is harvesting loss in bark an wood of about 10%. (BMLFUW 2016). The most commercial species are spruce (*Picea abies* (L.) H. Karst., 69%), European beech (*Fagus sylvatica* L., 7%) and Scots pine (*Pinus sylvestris* L., 6%) (BFW 2017).

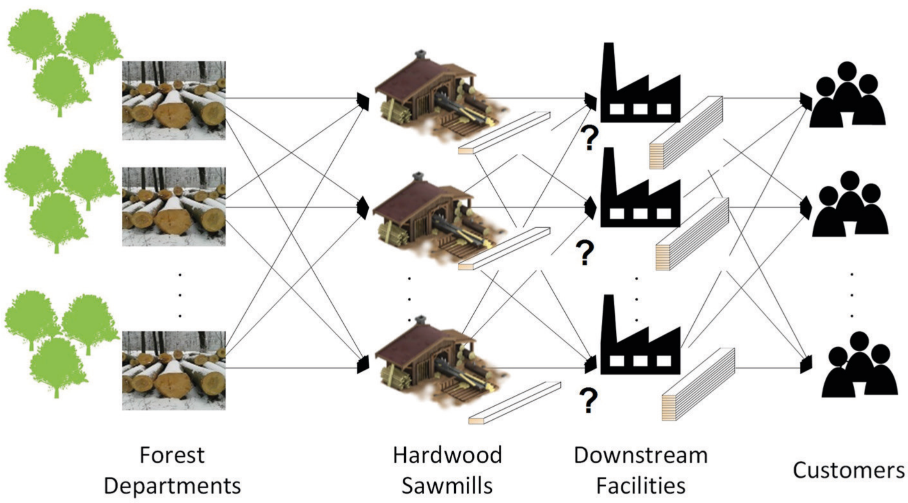


Fig. 1. The laminated beech wood supply network stakeholders and the material flows between them. There is a direct flow from one entity to all entities of the next tier. The source is at the forest departments and finishes at the sink, the customers. From several candidates, optimal downstream facilities are chosen to be opened within supply network.

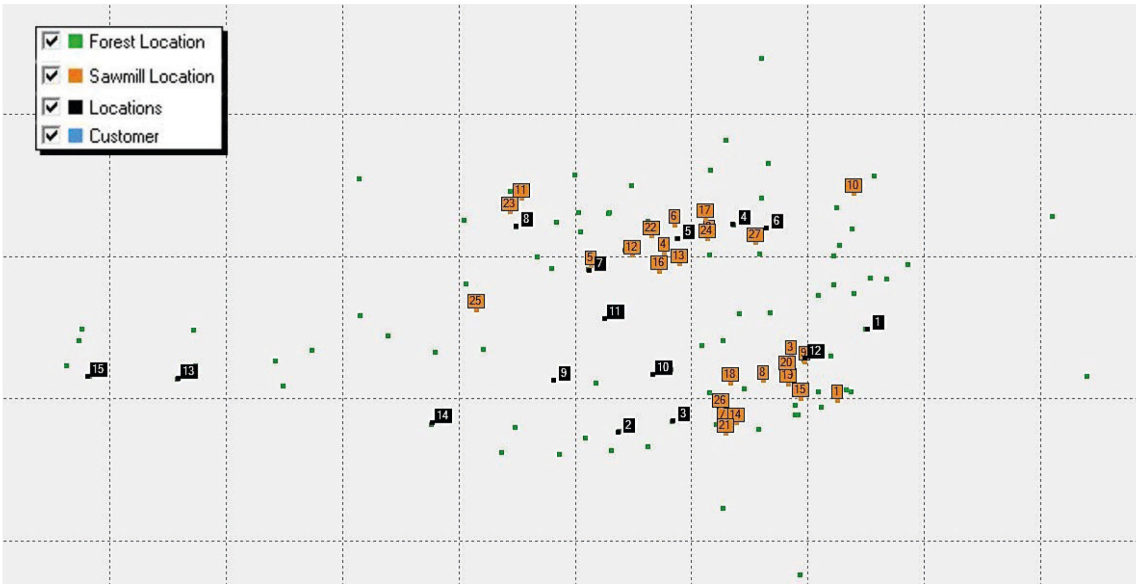


Fig. 2. The map represents the location of the several hardwood stakeholders. Forest departments with soft- and hardwood (green - 94), hardwood sawmills (orange - 27), laminated beech wood facility candidates (black -15) and customers (blue – have the same location as the forest departments - 88).

Deciduous trees are mainly located in the north-east and south-east of Austria. According to the Austrian forest inventory data of the period 2007–09, the four highest deciduous stocks are in Lower Austria, Styria, Upper Austria and Carinthia (BFW 2017). For the utilization of hardwood in 2015, Lower Austria used almost the same amount as all the other 8 federal states together. It is followed by Upper Austria, Styria and Burgenland. The amount of harvested hardwood for material utilization (mid-diameter > 20 cm) was 288 000 m^3 harvested timber of which approximately 146 000 m^3 of harvested timber was beech wood (BMLFUW 2016). In the model, 88 forest departments are considered which provide roundwood (Fig. 2). Their location is determined by the central global positioning system coordinates of the district cities. Hardwood amounts are differently distributed at each department and not every department supplies beech roundwood. The geographic orientation of Austria makes transnational raw material procurement necessary thus sawmills procure wood from adjacent countries like Germany or Hungary. If transnational raw material procurement from neighbor countries is also considered, an additional 212 730 m^3 are available (Table 1).

Table 1. Countries and amounts for beech roundwood procurement.

Country	City as central location	Share of beech in the country, estimated	Share of beech in the chosen location, estimated	Production, Sawlogs and veneer logs, non-coniferous* [m^3 of roundwood]	Amount of beech in the chosen location, calculated [m^3 of roundwood]
Slovakia	Nitra	25%	10%	1 558 996	38 975
Hungary	Székesfehérvár	6%	40%	919 400	22 066
Czech Republic	Iglau	8%	10%	496 000	3968
Germany	Landshut	18%	8%	3 356 883	48 339
Slovenia	Celje	30%	30%	320 823	28 874
Croatia	Zagreb	36%	10%	1 958 567	70 508
Total					212 730

* FAOSTAT

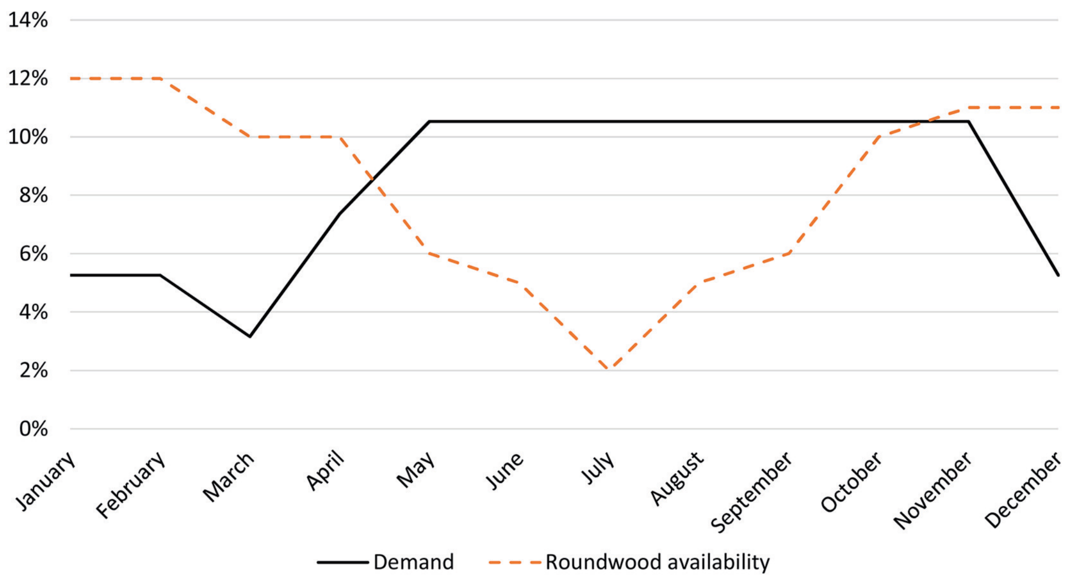


Fig. 3. Development of the annual product demand and the roundwood availability over the year.

In Fig. 3 the development of the yearly roundwood availability (12 periods) and the course of product demand is displayed. The values are used as a distribution key because the amounts of product demand and resources are only given per year.

2.1.2 Hardwood sawmills

The possible product amount depends on the availability of raw material, sawmill production capacities and demand. The Austrian hardwood sawmills have a wide range of production capacity. In 2015, 25–30 sawmills were operated with a sawing capacity from 1000 to 80 000 m^3 of roundwood (Holzkurier 2015). These hardwood sawmills are located almost in proximity to the forest resources. Less than half of the sawmills are in the north-east and less than a half are in the south-east of the considered region. In 2015 sawmills processed approximately 309 000 m^3 of roundwood. An estimated 132 000 m^3 of the annual hardwood roundwood amount is beech wood. If only sawmills are considered which have a higher production capacity than 4550 m^3 of roundwood each and manufacture beech, the result is an ultimate production capacity of 116 250 m^3 of roundwood per year. 4550 m^3 of saw logs are processed to a final product amount of 1000 m^3 of sawn timber using a material yield of 22% (η_1). Together, all hardwood sawmills can produce 275 500 m^3 of roundwood which have a higher production capacity than 4550 m^3 of roundwood each.

In addition to the already existing sawmills, another hardwood sawmill is introduced with the cutting capacity of 40 000 m^3 of roundwood, which is located in Lower Austria. It is assumed that sawmill production capacity is missing in the federal state of Austria with the highest deciduous stock.

For the sawmill production cost, Rathke et al. (2012) conducted a study about different hardwood sawing types and presented a cost parameter for band saws with cutting costs of 36.09 € m^{-3} of roundwood. In this paper, we chose 35 € m^{-3} for the annual production capacity interval from 25 000 to 45 000 m^3 of roundwood. Higher production capacities are calculated with 30 € m^{-3} and lower ones with 40 € m^{-3}. For sawmills with a production capacity under 10 000 m^3 of roundwood per year 45 € m^{-3} are used. The data can be modified for different planning purposes. Finally, an inventory is considered at the sawmills and downstream facilities which balances the fluctuation in raw material and products over the year by storing them to an earlier point of time if possible.

2.1.3 Laminated beech wood facilities (LBWF)

A modern LBWF satisfy a demand of 16–20 000 m^3 per year. As a reference, in Switzerland, the ultimate investment cost comes to 21.3 million CHF (19.9 million €) including real estate, infrastructure, machines for the production line as well as furnishings and equipment (Vögtli 2013). These costs are taken into account by annuity calculation over 20 years and a 5% interest rate.

For the supply chain model, 15 different locations where proposed as possible LBWF locations which are directly supplied by the sawmills. The facilities are distributed by following the two requirements: First, all federal states have to be considered and second, the locations have to be chosen with the lowest square meter purchasing price in the selected federal state. The yield recovery of the facility is determined with 95% (η_2). The 5% loss is related to the joining process only. Further, the facilities have different production capacity options (CAP_{lo}). Three types are determined with (O = 1) 20 000 m^3, (O = 2) 15 000 m^3 and (O = 3) 10 000 m^3. According to the size, the investment costs are adapted. These types represent only one shift. A second shift is selectable with three extra option (34 000 m^3 (O = 4), 25 500 m^3 (O = 5) and 17 000 m^3 (O = 6)). They are representing 170% of the original option capacity. These additional options do not influence the investments of the newly opened facility, but it may influence the facility location allocations and material flows because of the production capacity increase.

2.1.4 Customer demand

The demand for hardwood construction products is set to 50 000 m^3 per year. For laminated timber products, we guess that products of approximately 1.8 million m^3 were produced which mainly consist of softwood (Kaufmann et al. 2011). 50 000 m^3 are less than 3% substitution of the softwood laminated timber products. This amount is distributed all over Austria. The timber building distribution key of the survey was used to allocate the demand to the federal states. The detailed demand, within the Austrian federal states, is distributed over the several districts with the relation inhabitants per district. Also, a combined distribution key is determined for the national (40%) and transnational (60%) demand (Table 2).

Table 2. Demand distribution key for Austria (Kaufmann et al. 2011), Italy and Germany.

Countries	Scenario #1 – #13		Scenario #14	
Federal States	Weighting [%]	Amount [m^3]	Weighting [%]	Amount [m^3]
Austria	100.00	50 000	40.00	19 998
Lower Austria	21.52	10 760	21.52	4303
Upper Austria	17.01	8505	17.01	3403
Styria	16.53	8265	16.53	3306
Vienna	12.59	6295	12.59	2519
Tyrol	9.66	4830	9.66	1932
Carinthia	8.06	4030	8.06	1612
Salzburg	6.39	3195	6.39	1278
Burgenland	4.24	2120	4.24	844
Vorarlberg	4.00	2000	4.00	801
Italy	0	0	18.00	9000
Germany	0	0	42.00	21 000

2.1.5 Transportation data

In this paper a simplified transport situation is assumed. Three transport cost coefficients are determined with C1 (from forest department to sawmill), C2 (from sawmills to LBWF) and C3 (from LBWF to the customer). Each is made up of a unit cost per km divided by 28 m^3 of roundwood loading volume and multiplied by two for two directions. For C1 4 € m^3km^{-1}, for C2 3 € m^3km^{-1}, and C3 2.5 € m^3km^{-1} are assumed. For C1, the value computed is in line with the provided values from Borcherding (2007) for the driving distance between 50 to 100 km. The decreasing values for C2 and C3 simulate the increasing load density resulting from lower wood humidity and better packing potential through dimension formatting from the resource location to the customer. The applied simplicity either considers decreasing the cost for higher driven distances and no different vehicle possibilities (Suurs 2002).

2.2 Model description

We propose a mixed integer linear programming model (MILP) to find an optimal design for a general LBWSN considering the aforementioned entities. It combines a supply network flow with a FLP. The model aims to minimize the cost of supply network by satisfying a specific product demand per year. The model considers several parameters which characterize the four entities forest departments, sawmills, LBWF, and customers. Decision variables are introduced to describe material flows between the entities and within the sawmills and production facilities (Fig. 4).

The following section presents the exact formulation of the MILP model, defining sets, parameters [min; max], the objective function, decision variables, and constraints.

Indices

F	Set of forests departments
S	Set of sawmills
L	Set of laminated beech wood facility locations
C	Set of customers
O	Set of options
T	Set of periods

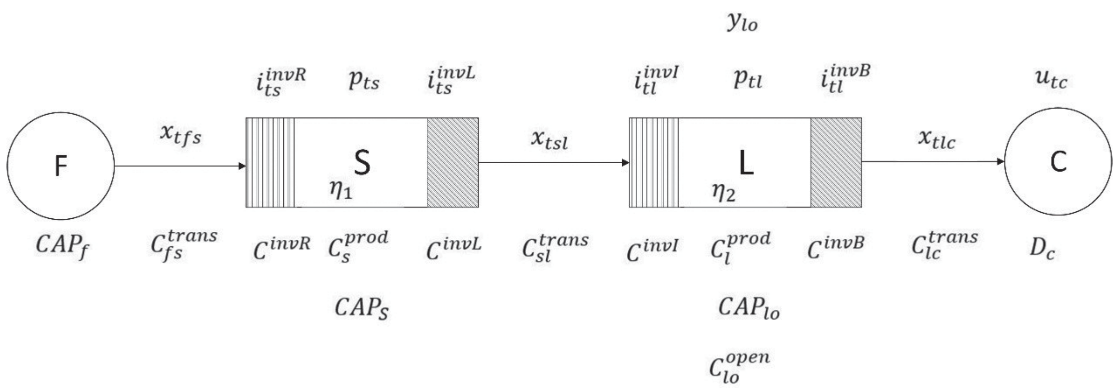


Fig. 4. Generic LBWSN with the four entities forest departments (F), hardwood sawmills (S), LBWF (L) and customers (C). I, p, u, x and y represent decision variables and the notations C and D represent parameters.

Parameters

C_{lo}^{open}	Fixed cost to open new LBWF location l with capacity option o [11 301 682 €; 14 941 682 €]
C_{fs}^{trans}	Transportation distance from forest f to sawmill s [0 km; 523 km]
C_{sl}^{trans}	Transportation distance from sawmill s to LBWF l [0 km, 507 km]
C_{lc}^{trans}	Transportation distance from LBWF l to customer c [0 km; 506 km]
C_{s}^{prod}	Unit sawing cost at sawmill s [30 €, 45 €]
C_{l}^{prod}	Unit production cost at LBWF l [30 €]
CAP_{tf}	Amount of resource at forest location f in period t [0 m^3 of roundwood; 8461 m^3 of roundwood]
CAP_{ts}	Production capacity at sawmill s in period t [0 m^3; 7083 m^3]
CAP_{lo}	Production capacity at LBWF l with capacity option o [833 m^3; 2125 m^3]
D_{tc}	The demand of Customer in period t [0 m^3; 2211 m^3]
L_{max}	Max amount of new LBWF [0; 15]
M	High value [400]
C^{invR}	Unit inventory cost for raw material at sawmill [12 €]
C^{invL}	Unit inventory cost for the product at sawmill [10 €]
C^{invI}	Unit inventory cost for raw material at LBWF [10 €]
C^{invB}	Unit inventory cost for the product at LBWF [8 €]
C_1,C_2,C_3	Transport cost coefficient [0.2856 € m^3km^{-1}, 0.071 € m^3km^{-1}, 0.178 € m^3km^{-1}]
η_1	Yield at sawmills to disassembly hardwood stems to timber [0.22]
η_2	Yield at LBWF to assembly hardwood timber to beams [0.95]
S^{invR}	Start inventory for raw material at sawmill [0 m^3 of roundwood]
S^{invL}	Start inventory for the product at a sawmill [0 m^3]
S^{invI}	Start inventory for raw material at LBWF [0 m^3]
S^{invB}	Start inventory for product at LBWF [0 m^3]

Variables

x_{tfs}	Amount of roundwood shipped from forest f to sawmill s in period t [m^3]
x_{tsl}	Amount of lamellas shipped from sawmill s to LBWF l in period t [m^3]
x_{tlc}	Amount of product shipped from LBWF l to customer c in period t [m^3]
p_{ts}	Amount of consumed roundwood at sawmill s in period t [m^3]
p_{tl}	Amount of consumed lamellas at LBWF l in period t [m^3]
i_{ts}^{invR}	Inventory level of raw material at sawmill s in period t [m^3 of roundwood]
i_{ts}^{invL}	Inventory level of product at sawmill s in period t [m^3]
i_{tl}^{invI}	Inventory level of raw material at LBWF l in period t [m^3]
i_{tl}^{invB}	Inventory level of product at LBWF l in period t [m^3]
y_{lo}	1, if LBWF l is open with capacity option o, 0 otherwise
u_{tc}	Unsatisfied demand of customer c in period t

2.2.1 Objective function

The objective function is to minimize the total cost of the supply network. The costs of the model comprise sawing at the sawmills, transportation, production at the LBWF, inventory, demand shortage and fixed cost to open new LBWF (1).

$$\begin{aligned}\min(z) = &\sum_{t\in T,c\in C} M * u_{tc} + \sum_{t\in T,f\in F,s\in S} C_1 * C_{fs}^{trans} * x_{tfs} \\ &+ \sum_{t\in T,s\in S,l\in L} C_2 * C_{sl}^{trans} * x_{tsl} + \sum_{t\in T,l\in L,c\in C} C_3 * C_{lc}^{trans} * x_{tlc} \\ &+ \sum_{t\in T,s\in S} C_s^{prod} * p_{ts} + \sum_{t\in T,l\in L} C_l^{prod} * p_{tl} + \sum_{t\in T,s\in S} C^{invR} * i_{ts}^{invR} \\ &+ \sum_{t\in T,s\in S} C^{invL} * i_{ts}^{invL} + \sum_{t\in T,l\in L} C^{invI} * i_{tl}^{invI} + \sum_{t\in T,l\in L} C^{invB} * i_{tl}^{invB} \\ &+ \sum_{l\in L,o\in O} C_{lo}^{open} * y_{lo}\end{aligned} \tag{1}$$

The decision variable u_{tc}, is used to guaranty maximal demand satisfaction. There will be model configurations which do not satisfy the demand constraint thus a model objective value of 0 will be provided. To counteract this effect, the decision variable u_{tc} is introduced thus also a not fully achieved demand satisfaction will provide a solution.

2.2.2 Constraints

Constraint (2) and (3) provide the production and supply capacity constraint.

$$\sum_{s\in S} x_{tfs} \le CAP_{tf} \quad \forall t\in T, \mathrm{f}\in \mathrm{F} \tag{2}$$

$$p_{ts} \le CAP_{ts} \quad \forall t\in T, \mathrm{s}\in \mathrm{S} \tag{3}$$

$$i_{ts}^{invR} = i_{(t-1)s}^{invR} + \sum_{f\in F} x_{tfs} - p_{ts} \quad \forall t\in T, \mathrm{s}\in \mathrm{S} \mid \mathrm{t}>1 \tag{4}$$

$$i_{ts}^{invR} = S^{invR} + \sum_{f\in F} x_{tfs} - p_{ts} \quad \forall t\in T, \mathrm{s}\in \mathrm{S} \mid \mathrm{t}=1 \tag{5}$$

$$i_{ts}^{invL} = i_{(t-1)s}^{invL} - \sum_{l\in L} x_{tsl} + \eta_1 * p_{ts} \quad \forall t\in T, \mathrm{s}\in \mathrm{S} \mid \mathrm{t}>1 \tag{6}$$

$$i_{ts}^{invL} = S^{invL} - \sum_{l\in L} x_{tsl} + \eta_1 * p_{ts} \quad \forall t\in T, \mathrm{s}\in \mathrm{S} \mid \mathrm{t}=1 \tag{7}$$

$$i_{tl}^{invI} = i_{(t-1)s}^{invI} - \sum_{s\in S} \eta_2 * x_{tsl} - p_{tl} \quad \forall t\in T, \mathrm{l}\in \mathrm{L} \mid \mathrm{t}>1 \tag{8}$$

$$i_{tl}^{invI} = S^{invI} - \sum_{s\in S} \eta_2 * x_{tsl} - p_{tl} \quad \forall t\in T, \mathrm{l}\in \mathrm{L} \mid \mathrm{t}=1 \tag{9}$$

$$i_{tl}^{invB} = i_{(t-1)s}^{invB} - \sum_{c\in C} x_{tlc} + p_{tl} \quad \forall t\in T, \mathrm{l}\in \mathrm{L} \mid \mathrm{t}>1 \tag{10}$$

$$i_{tl}^{invB} = S^{invB} - \sum_{c\in C} x_{tlc} + p_{tl} \quad \forall t\in T, \mathrm{l}\in \mathrm{L} \mid \mathrm{t}>1 \tag{11}$$

$$\sum_{l\in L,o\in O} y_{lo} \le L_{\max} \tag{12}$$

$$\sum_{o\in O} y_{lo} \le L \quad \forall \mathrm{l}\in \mathrm{L} \tag{13}$$

$$p_{tl} \le \sum_{o\in O} CAP_{lo} * y_{lo} \quad \forall \mathrm{t}\in \mathrm{T}, \mathrm{l}\in \mathrm{L} \tag{14}$$

$$\sum_{l\in L} x_{tlc} + u_{tc} = D_{tc} \quad \forall \mathrm{t}\in \mathrm{T}, \mathrm{c}\in \mathrm{C} \tag{15}$$

$$y_{lo} \in \{0,1\} \quad \forall \mathrm{l}\in \mathrm{L}, \mathrm{o}\in \mathrm{O} \tag{16}$$

$$i_{ts}^{invR},\ i_{ts}^{invL},\ i_{tl}^{invI},\ i_{tl}^{invB},\ x_{tfs},\ x_{tsl},\ x_{tlc},\ p_{ts},\ p_{tl},\ u_{tc} \ge 0 \tag{17}$$

Constraint (4) to (11) assure that the material flow is balanced at the different positions. For the several periods, the sum of incoming and outgoing material flows has to be zero. Constraints (4), (6), (8) and (10) represent the inventory levels for the periods higher than one, while every other constraint represents the inventory level for the first periods. Thus, the start inventory S^{inv} is introduced. Constraint (12) can be used to limit the number of LBWF. Every opened LBWF has just one production capacity option (13). Constraint (14) assures that the available LBWF production capacity with option o can not exceeded. Constraint (15) defines the demand satisfaction constraints stating that the determined demand is every time satisfied by the sum of the product shipment and the unsatisfied demand variable. Finally, variables are defined in constraint (16) and (17).

2.3 Numerical experiments and scenario setup

In order to test the sensitivity of the optimal LBWSN design, several assumptions are made for key parameters of the network stakeholders. Opening a LBWF is linked with a high fixed cost. Therefore, the scenarios are used to examine if a facility location is competitive under various configuration. Altogether, 14 individual scenarios are designed. The matrix of scenarios is provided in Table 3.

The first two scenarios represent the current situation of the network. They consider only beech processing sawmills and a national sourcing strategy (SO with AUT) with an amount of roundwood (AR) of 146 023 m^3. The difference to the first scenario (#1) is that the #2 has a minimal production capacity threshold of 4550 m^3 of roundwood.

For the following scenarios, the sawmill production capacity is increased in total by using all hardwood sawmills for the converting of beech wood. The existing cutting technologies would make it possible to change the hardwood type.

#3 represents the new adaption of the total sawmill capacity. In #4, it is possible to have a LBWF with six different production capacities options (FCO).

In #5 and #6, the additional hardwood sawmill (AS) is used.

Table 3. Developed scenarios with the defined parameters.

Scenarios	Additional sawmill (ADS)	Amount of facilities (AF)	Facility capacity option (FCO)	Sourcing strategy (SO)	Amount of roundwood (AR)
#1		unlimited	3	AUT	146 023
#2		unlimited	3	AUT	146 023
#3		unlimited	3	AUT	146 023
#4		unlimited	6	AUT	146 023
#5	x	unlimited	3	AUT	146 023
#6	x	unlimited	6	AUT	146 023
#7	x	unlimited	3	AUT + Neighbours	358 762
#8	x	unlimited	6	AUT + Neighbours	358 762
#9	x	1	3	AUT + Neighbours	358 762
#10	x	1	6	AUT + Neighbours	358 762
#11		unlimited	3	AUT + Neighbours	358 762
#12	x	unlimited	3	AUT + Neighbours	358 762
#13	x	unlimited	6	AUT + Neighbours	358 762
#14	x	unlimited	6	AUT + Neighbours	358 762

#7 to #8 are based on the previous assumptions plus a transnational sourcing strategy (SO AUT + Neighbours). This sourcing strategy is also assumed for the following scenarios. On the one hand, there would not be enough beech roundwood to fulfill all demand with a national one. On the other hand, a shorter distance can be used.

For #9 to #10, it is assumed that the amount of LBWF (AF) is limited to one. The high financial risk of the investment and the uncertain demand makes it more reasonable to open only one facility and to accept the unsatisfied demand.

#11 to #13 represent the configuration of an alternative network design based on the existing sawmill locations but with increased production capacities. Additional to the LBWF capacities also sawmills capacities can be modified; thus the LBWSN is re-engineered by optimized material flows. The #13 configuration includes all 27 hardwood processing sawmills. Their cutting capacities are set to 20 000 m^3 of roundwood at least. The investment costs for the required technology adoption are not considered in the model. The focus is based on the minimal supply network cost and the design with the corresponding material flow.

The last configuration (#14) is similar to #13. Only the national and transnational demand is different. 40% of the demand is located in Austria, and 60% are located in Germany (70%) and Italy (30%).

For every modification according to the scenario configuration, a MILP model is calculated and resolved again.

After the calculation, the results are presented and analyzed in two steps. The first represents cost parameters which are given in € m^{-3} for the satisfied individual demand per scenario. There are the total cost (objective value minus the unsatisfied cost), the opening cost for the chosen amount of facilities and the capacity option, the transport cost from each used entity, the production cost (sawing cost at sawmills and production cost at the LBWF) and the combined storage cost for sawmill and LBWF. The second part shows material parameters in % per scenario. The degree of production capacity utilization for individual sawmills is shown with a bar chart and which LBWF is opened.

The model is implemented in the modeling language Xpress Mosel Version 4.0.0 using FICO Xpress-Optimizer 29.01.07 as a solver. All numerical tests were run on a standard laptop with a 2.8 GHz processor and 48.0 GB RAM.

3 Results

The solver runtime never lasts more than 40 sec for the given problem size. For example, the model counts 53 814 variables, 3304 constraints and 107 124 non-zero elements in #13.

The graphical output, for #1, shows that the sawmills are located in the north-east or south-east. Also, the LBWF has a south-east location in the network (Fig. 5).

The total supply costs per satisfied demand of laminated beech products range from 309 to 351 € m^{-3} and the satisfied demands range from 14 847 to 38 242 m^3 (Table 4).

The lowest opening cost is calculated for #14 with 27 € m^{-3}. This means that 27 € m^{-3} of the cost is investment cost. Also, they have the lowest transportation cost but not the lowest demand satisfaction. #2 represents the lowest demand satisfaction and minimal production cost over all calculations. It is the scenario with the lowest production capacity. Thus only sawmills are considered which cut beech and have a production capacity threshold of 4550 m^3 of roundwood. #2 also has the highest total cost of supply.

Considering the production costs in contrast to the remaining costs, Fig. 6 illustrates that production cost makes up around half of the total supply cost but reaches two thirds in scenario #6. The storage cost can be neglected because they take a very small share of the remaining supply costs.

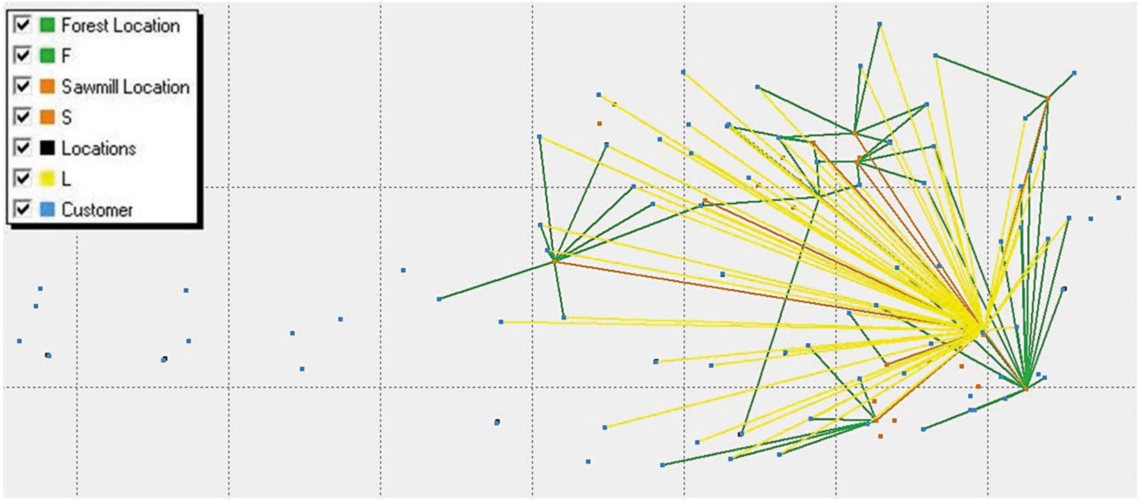


Fig. 5. Material flow of #1. The individual colours illustrate the material flows from forest locations to sawmills (green), from sawmills to facility locations (orange) and from facility location to customer (yellow).

Table 4. Financial performance results for scenarios #1 to #14.

Cost parameter	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14
Sadiesfied demand [m^3]	14972	14847	23942	26639	24181	24378	30000	33451	19992	31092	34703	34710	37548	38242
Total supply cost per m^3 [€ m^{-3}]	345	351	339	332	324	309	330	322	311	323	341	331	323	321
Opening cost [€ m^{-3}]	48	49	53	41	53	30	49	33	46	30	47	47	34	27 €
Transport cost [€ m^{-3}]	109	121	79	86	71	76	87	94	70	92	92	87	92	93 €
Production cost [€ m^{-3}]	186	178	202	202	195	198	191	191	193	197	197	192	192	197 €
Storage cost [€ m^{-3}]	2	2	5	2	5	5	4	4	2	5	5	5	4	4 €

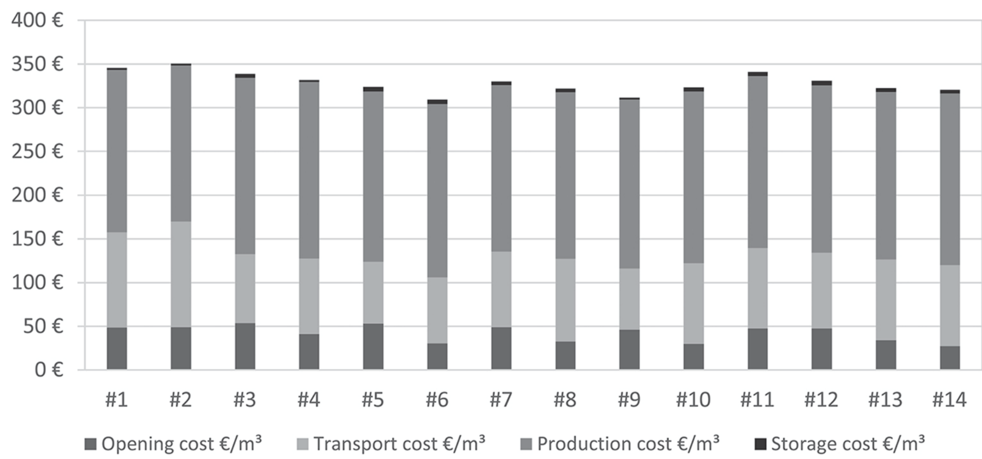


Fig. 6. The total supply network costs are represented per satisfied demand and for each sceanrio.

Table 5. Material performance results for scenarios #1 to #14.

Material parameter	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14
Degree of demand fulfillment [%]	30	30	48	53	48	49	60	67	40	62	69	69	75	76
Amount of used resources [%]	49	49	78	87	79	80	40	45	27	41	46	46	50	51
Amount of imported resources [%]	0	0	0	0	0	0	25	27	6	17	25	24	27	28
Amount of used saw-mill capacity [%]	54	61	42	46	37	37	45	51	30	23	27	26	28	28
Amount of used LBWF capacity [%]	100	99	60	78	69	98	100	98	100	91	99	87	88	75

The material performances are shown in Table 5 for all calculations. For four chosen scenarios, Fig. 7 shows the satisfied demand and resource supply over the year. They are chosen because #6 has the lowest total cost of supply, #8 has no sawmill capacity adaption but transnational sourcing, in #9 only one LBWF can be opened, and in #13 the highest resource, sawmill and LBWF capacities are available. The degree of demand fulfillment is at the lowest point in #1 and #2 and increased gradually from 30% up to 76%. The expansion of the roundwood sourcing locations and amounts shows also a change in the amount of used resources from #6 to #7. The amount of imported roundwood reaches 28% in #14. The highest utilization of the sawmill capacities is in #2 with the lowest sawmill capacity in total. Almost all opened LBWF have a high capacity utilization. Three even reach the capacity limit.

Fig. 7. Material performance results are shown for scenario 6, 8, 9 and 13. The raw material (orange,) and demand of products (black, m^3 of product, right diagram title) curves result from the key distribution parameter and have the same development in the four diagrams. In contrast to the following three scenarios, #6 includes a national souring only. Roundwood (grey, m^3 roundwood, left diagram title) product transportation (red, m^3 of product, right diagram title) are the results of the individual scenarios.

Over the year, the curves for customer demand and availability of resource proceed in opposite directions. While the demand of laminated wood products for construction purposes has high season over summer, roundwood availability has low season.

For #6 in Fig. 7, the demand is almost satisfied for the first three months and roundwood is provided at a high level. Up to April, the demand recovers after a demand downturn in March, but the product supply stays low the following months. With the assumption of transnational roundwood procurement, which achieves a higher roundwood amount, the demand is satisfied on a higher level (#8). If the amount of new LBWF is limited, also the supply of products to customer is limited and fixed on a specific level (#9 with only one LBWF). With the possibility of more sawmills with cutting capacity over 20 000 m^3 of roundwood, the demand can be satisfied on a high level with roundwood procurement shortage in July (#13).

To understand the sawmill side and the integration of each sawmill into the supply network designs, the operated sawmills are presented in Fig. 8. Additionally, the degree of capacity utilization is shown and the opened LBWF are represented. The additional sawmill 27 is always used if it is possible and it always reaches the capacity limit. Considering the specific used sawmills in the scenarios, it is obvious that also in #11 to #14 the same sawmills are used than in the scenarios before, although every sawmill location is available to produce lamellas and that with a raised threshold.

With the focus on open a LBWF within the supply network, the scenarios calculated two optimal locations for the facilities for #1 to #13 and an additional one for the #14. One, L 12, is located in Styria and the second one, L 4, is located in Lower Austria and the third one, L 8, is located in Upper Austria.

Finally, different limits occur within the scenarios. The first two scenarios show a very low degree of demand fulfillment by a high total cost of supply and a high percentage of used sawmill capacity. The provided sawmill capacity is the limit for these scenarios because the distances and transport cost also increase with a higher sawmill capacity use. More roundwood is used in the next four scenarios because higher production capacity is available at the sawmills; thus it results in a higher demand fulfillment and lower total supply cost. Here, the roundwood is at the highest consumption compared to the other scenarios. For the following scenarios, the degree of demand fulfillment illustrates the limit. It is at the highest level compared to the previous scenarios.

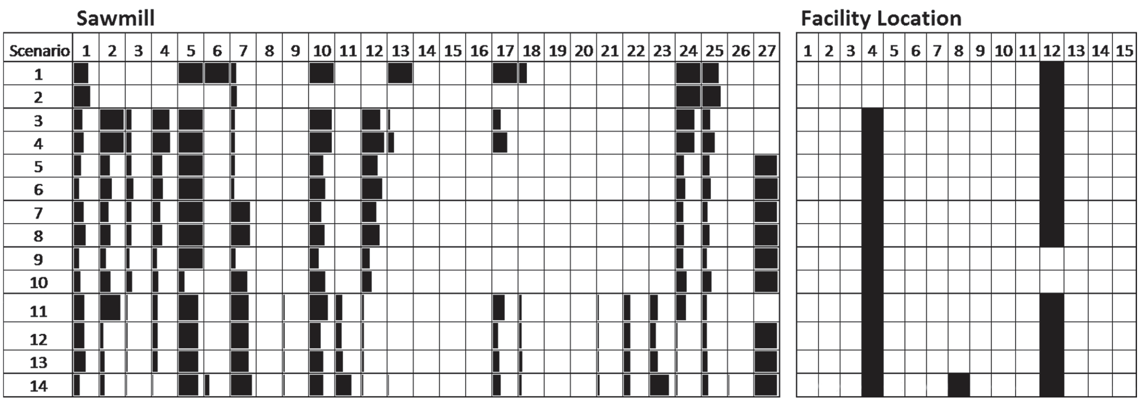


Fig. 8. For all 14 scenarios, the used sawmills and facilities are represented. For the facility locations, it is just shown if it is opened. The degree of sawmill capacity utilization is shown with percentage bar sizes. The additional sawmill 27 is used every time when it was possible.

4 Discussion and conclusions

With the developed approach, proposed in the current paper, the LBWSN flows from forest departments via hardwood sawmills and the optional downstream facility for construction purpose to the final customer, can be optimized. Also, different scenarios are presented which simulate specific assumptions to support the optimization and the evaluation of the supply chain network designs. In most practical situations, a quite large number of scenarios is possible but only a few of them can be considered in the optimization process for reasons of time. With the focus on opening up a LBWF within the supply network, two locations are calculated repetitive for optimal locations in the several scenarios. Further aspects will be discussed which result from the outcome of the scenarios and which are linked to the developments in the LBWSN.

4.1 Sawmill characterization and LBWF location

Both opened facilities have bigger suppliers of lamellas in their closer distance which result in lower transport and production cost. Further, the used sawmill can be classified in three groups: sawmills which I) manufacture beech and have a production capacity equal or higher 20 000 m^3 of roundwood, II) manufacture beech and have a production capacity lower 20 000 m^3 of roundwood or III) manufacture no beech and have a production capacity lower 20 000 m^3 of roundwood. The last two groups of sawmills need a raise of production capacity like new or enhanced technology. This can benefit the owner and the whole LBWSN, but it challenges the hardwood network which contains of stakeholders with own objectives. Thus in the most cases, it is easier to design a new network from scratch than to reengineer it. Optimizing existing processes means that new processes have to be integrated in running operations and the transition has to be well planned from one to the other network design. In this work, an addition sawmill was integrated to study the impact on the network (Fig. 8, sawmill 27). Besides the full use of its capacity, the opening of the sawmill can reduce the network production and transport costs 5 € m^{-3} each (Table 4, #11 and #12).

4.2 The inventory role

The possibility to store raw materials and products has an impact to satisfy the demand. Inventory plays an important role in this network and model because roundwood and products are stored to provide them when they are needed. The availability of roundwood is decreasing from spring time and whereas the demand from the side of the sawmills starts to raise. Fig. 7 represents how the material flows react to the situation and with the high demand gradient from the beginning of spring. For example #13, the production capacity is limited to 3541 m^3 for the assigned LBWF. After the demand gap in March, the satisfied demand went over the production capacity. Products and raw material are used from the storage to satisfy demand. After May, the curve goes down because roundwood is not economically available anymore although demand of final products and roundwood are still existing. It is to point out that the model has no storage limit constraints, but they could be added easily.

4.3 Raw material increase and the influence on the supply network

By design, the optimization model focusses on strategic planning to choose the optimal LBWF locations and material flow within the production network. For the model, the period of scope is one year with 12 periods. It does not consider future resource increment of the local forest sources. For the investors, the investment horizon is an important aspect which can be 15 years and more.

Studies show that there is an increase in hardwood stocks and that the trend goes on. This has an impact on the overall supply network cost. To anticipate the consequences for this cost, the national (#5 and #6) and transnational (#7 and #8) sourcing strategy are compared. It can be assumed that the production cost will decrease per m³, the opening cost stays stable (decrease from #5 to #7 and increase from #6 to #8) and the satisfied demand will increase. Transportation cost increase because of the longer roundwood allocation distances and in order to supply more customers. It is to be highlighted that this increases the degree of demand fulfillment by 18% (#6 to #8). In total the overall cost of transport increases from 76 € m^{-3} (#6) to 87 € m^{-3} (#8). It can be assumed that saw log transport cost will decrease with a higher amount of local resources available. Nevertheless, it is possible to work out further cost reduction when the procurement part is investigated in more detail. Potential can be found in the use of different means of transports, the strategy of sourcing like collective procurement of logs or further advanced transport tactics like back hauling.

4.4 Change of demand

In this paper, demand was determined to 50 000 m^3 glued laminated beech wood products. In the same way as the resource amount, also the demand side can not be predicted with certainty. In the case the demand would be higher than expected, it would strongly affect the network structure. In the case, laminated wood product demand increases from 3% to 10%, as an example, this can result in economy of scale effects which will affect the total supply chain costs as described by Song and Sun (2016).

Italy and Germany are the major buyers of Austrian wood-products. Therefore, 60% of the demand are located transnationally. When the additional demand is considered in the calculations, this results in a slightly different network design and material flow. The satisfied demand reaches 76% (#14), which is 1% more than for the national demand only. Like before, the additional sawmill 27 is used. For the opened LBWF, it is noticeable that facility 8 (Upper Austria) is opened in addition to 4 and 12. The opening cost are the lowest for all scenarios, although it is optimal to open three facilities which result in a lower amount of used facility capacity. The total supply cost makes up 321 € m^{-3} and the transport cost 93 € m^{-3}. With the computed results, the #14 is in accordance with the other 13 scenarios.

4.5 Managerial implication

Data, which is visualized in Fig. 8, can support the decision which stakeholders should be cooperating to guaranty reduced network and product costs. Results about used and transported amounts as well as used forest departments, sawmills, opened facilities and customer locations are available, which lead to optimized material flows through the supply network. One important insight is that the production of laminated beech wood products has to be a cooperative planning between existing stakeholder and new ones. Instead of individual stakeholder goals, we defined an overall supply network objective. The potential LBWSN can lead to sawmills with qualitative manufacturing and secure supply of beech lamellas and to LBWF which are focused on producing qualitative laminated beech wood products and satisfying final customers.

4.6 Further outcomes

This paper looks at the minimal supply network cost from raw material to the customer and integrated transportation as well specific manufacturing activities of the production units. Beyond the paper of Torno et al. (2013), this paper integrated the decision to open downstream facilities at determined locations as well as transportation activities between the units and before and after the sawmills. Further, this paper considered location positions of the production units as well as capacity differentiations of the sawmills and the LBWF.

Ouhimmou et al. (2008) conducted an analyze of a specific furniture company by using their internal dataset and compared computed results with the results of the company planning process. The provided dataset helped the authors to find potential performance improvements. The main reason for the improvements increase was fitting sawing policies and hardwood logs to the customer´s demand configuration. In this paper, only one material yield is used for the sawing process for one class of beech logs which was provided by Torno et al. (2013). At this point, there is potential for further studies which should consider different sawing policies for various log dimensions or alternative sawing policies which go along with the new intermediate products. Also, if there is a deeper study of the laminated beech wood supply network, it will be necessary to conduct a broader study for collaboration between the beech wood production units either through information or resource sharing. D´Amours and Rönnqvist (2008) report that this results in decreased cost of executing the logistics activities, improve service, gain market shares, enhance capacities as well as protect environment and mitigate climate change Issues. Just as authors before, Abasian et al. (2017) reported that collaboration has a significant effect on the supply network profit.

As well as Feng et al. (2010) emphasize it, this model is also capable in evaluating various network designs with depended production unit parameters and amounts to find the minimal cost of the supply network, but the results are scenario sensitive. Therefore, further particular business data is required as well as scenario studies.

5 Concluding remarks

In general, this work provides data to the solid hardwood business and develops a MILP model in order to design a LBWSN. For a new product in the hardwood sector, the model covers the important strategic decision where to locate a glued laminated wood facility within the existing production network with the lowest supply network cost. The results of the optimization model, e.g. material flows and sawmills involved, can be considered for further planning. From the allocation of a production site, the continuous laminated beech wood production has to be guaranteed by a secure lamella supply by the sawmills. It will be challenging to develop a cooperation planning of the network actors on a tactical and operational level. Papers, which already tackled aforementioned aspects, show that a comprehensively developed model with well detailed data can identify further potentials in unused capacities. Thus, simultaneous considerations of the mechanical, production and network aspects will lead to further cost reductions within the LBWSN (Audy et al. 2012; Ouhimmou et al. 2008).

Acknowledgements

This paper is supported by BOKU Vienna Open Access Publishing Fund. Financial support for the work done in the framework of the PhD School DokIn´Holz was also provided by the Austrian Federal Ministry of Science, Research and Economy as well as the Austrian Federal Forestry Office and the Austrian Chamber of Agriculture are gratefully acknowledged.

References

Abasian F., Rönnqvist M., Ouhimmou M. (2017). Forest fibre network design with multiple assortments: a case study in Newfoundland. Canadian Journal of Forest Research 47(9): 1232–1243. https://doi.org/10.1139/cjfr-2016-0504.

Alayet C., Lehoux N., LeBel L. (2018). Logistics approaches assessment to better coordinate a forest products supply chain. Journal of Forest Economics 30(1): 13–24. https://doi.org/10.1016/j.jfe.2017.11.001.

Audy J.-F., Lehoux N., D'Amours S., Rönnqvist M. (2012). A framework for an efficient implementation of logistics collaborations. International Transactions in Operational Research 19(5): 633–657. https://doi.org/10.1111/j.1475-3995.2010.00799.x.

Berendt F., Fortin M., Jaeger D., Schweier J. (2017). How climate change will affect forest composition and forest operations in Baden-Württemberg—a GIS-based case study approach. Forests 8(8): 298. https://doi.org/10.3390/f8080298.

BFW (2017). Die österreichische Waldinventur. Erhebung 2007–09. [Austrian forest inventory]. Ascertainment 2007–09. Bundesforschungs- und Ausbildungszentrum für Wald, Naturgefahren und Landschaft. http://bfw.ac.at/rz/wi.home. [Cited 4 Jun 2017]. [In German].

Blenk M., Wehrmann W., Torno S. (2015). Laubholz für tragende Konstruktionen – Zusammenstellung zum Stand von Forschung und Entwicklung. [Hardwood for load-bearing constructions – Compilation on the state of art in research and development]. Cluster-Initiative Forst und Holz in Bayern gGmbH. [In German].

BMEL (2017). Forests and forest policy in Germany. Hg. v. BMEL. Federal Ministry of Food and Agriculture, Bonn.

BMLFUW (2015a). Austrian forest report 2015. Hg. v. Johannes Prem. BMLFUW – Federal Ministry of Agriculture, Forestry, Environment and Water Management, Vienna.

BMLFUW (2015b). Nachhaltige Waldwirtschaft in Österreich. Datensammlung zum österreichischen Wald. [Sustainable forestry in Austria. Data collection on the Austrian forest]. Time series for hardwood harvesting. BMLFUW – Federal Ministry of Agriculture, Forestry, Environment and Water Management, Vienna. 295 p. [In German].

BMLFUW (2016). Holzeinschlagsmeldung für das Jahr 2015. [Austrain logging report for 2015]. BMLFUW – Federal Ministry of Agriculture, Forestry, Environment and Water Management. https://www.bmnt.gv.at/dam/jcr:6bdf0ab0-d247-45b8-b5f9-83e419000069/Daten%20Holzeinschlag%202015%20BF%20CI.xlsx. [Cited 20.02.2017]. [In German].

Borcherding M. (2007). Rundholztransportlogistik in Deutschland – eine transaktionskostenorientierte empirische Analyse. [Log transport logistics in Germany – a transaction cost-oriented empirical analysis]. Dissertation. University of Hamburg, Hamburg. 266 p. [In German].

D´Amours S., Rönnqvist M. (2008). Issues in collaborative logistics. SNF Report 27/08. ISBN 978-82-491-0608-0. Institute for Research in Economics and Business Administration, Bergen. 19 p.

Drucker P.F. (1995). The information executives truly need. Harvard Business Review 1995: 54–62.

Espinoza O., Buehlmann U. (2018). Cross-laminated timber in the USA. Opportunity for hardwoods? Current Forestry Reports 4(1): 1–12. https://doi.org/10.1007/s40725-018-0071-x.

FAOSTAT (2017). Domain code: FO (forestry production and trade); Area code: 11,79,97,98,167,198,199; Element code: 5516 (production); Item code: 1604 (sawlogs and veneer logs, non-coniferous); Year: 2015; Unit: m^3. http://www.fao.org/faostat/en/#data/FO. [Cited 22 May 2017].

Farahani R.Z., Seifi M.S., Asgari B. (2010). Multiple criteria facility location problems: a survey. Applied Mathematical Modelling 34(7): 1689–1709. https://doi.org/10.1016/j.apm.2009.10.005.

Feng Y., D'Amours S., LeBel L., Nourelfath M. (2010). Integrated bio-refinery and forest products supply chain newtork design using mathematical programming approach. CIRRELT-2010-50. https://doi.org/10.13140/RG.2.1.1979.2081.

Gronalt M., Rauch P. (2007). Designing a regional forest fuel supply network. Biomass and Bioenergy 31(6): 393–402. https://doi.org/10.1016/j.biombioe.2007.01.007.

Holzkurier (2015). Laubholzsägewerke Deutschland und Österreich: 2015. [Hardwood sawmills in Germany and Austrian in 2015]. Holzkurier 2015(38): 15–17. [In German].

Johnson D.M., Jenkins T.L., Zhang F. (2014). Methods for optimally locating a forest biomass-to-biofuel facility. Biofuels 3(4): 489–503. https://doi.org/10.4155/bfs.12.34.

Kanzian C., Kühmaier M., Zazgornik J., Stampfer K. (2013). Design of forest energy supply networks using multi-objective optimization. Biomass and Bioenergy 58: 294–302. https://doi.org/ 10.1016/j.biombioe.2013.10.009.

Kaufmann H., Nerdinger W., Grdanjski M., O'Donovan J.R., Robinson M., Taylor J., Kühfuss M. (2011). Bauen mit Holz. Wege in die Zukunft. Österreischiche Informationsbeilage. [Building with timber. Paths into the future]. Austrian information supplement. Prestel, Munich. [In German].

Klibi W., Martel A., Guitouni A. (2010). The design of robust value-creating supply chain networks. A critical review. European Journal of Operational Research 203(2): 283–293. https://doi.org/10.1016/j.ejor.2009.06.011.

Krackler V., Keunecker D., Niemz P., Hurst A. (2011). Possible field of hardwood application. Wood Research 56(1): 125–136.

Lehner L., Kinnunen H., Weidner U., Lehner J., Pauli B., Menk J. (2014). Branchenanalyse. Analyse und Synthese der Wertschöpfungskette (WSK) Wald und Holz in der Schweiz. [Industry analysis. Analysis and synthesis of the value chain (VC) forest and wood in Switzerland]. bwc management consulting GmbH. [In German].

Mansoornejad B. (2012). Design for flexibility in the forest biorefinery supply chain. Dissertation. École Polytechnique de Montréal, Départment de génie chimique, Canada.

Melo M.T., Nickel S., Saldanha-da-Gama F. (2009). Facility location and supply chain management – a review. European Journal of Operational Research 196(2): 401–412. https://doi.org/10.1016/j.ejor.2008.05.007.

Ouhimmou M., D'Amours S., Beauregard R., Ait-Kadi D., Chauhan S.S. (2008). Furniture supply chain tactical planning optimization using a time decomposition approach. European Journal of Operational Research 189(3): 952–970. https://doi.org/10.1016/j.ejor.2007.01.064.

proHolz (2013). Im Wald. [In the forest]. Zuschnitt 51. http://www.proholz.at/shop/publikation-detail/kategorie/zuschnitt/produkt/zuschnitt-51/. [Cited 20 Feb 2017]. [In German].

Rathke J., Huber H., Teischinger A., Müller U., Hansmann C. (2012). Verwendbarkeit von Laubschwachholz in der Sägeindustrie. Teil 1: Ausbeuteberechnung und Technologiebewertung. [Utilization of small dimensioned hardwood in the sawmill industrie]. Holztechnologie 51 (6). [In German].

Rauch P., Gronalt M. (2010). The terminal location problem in the forest fuels supply network. International Journal of Forest Engineering 21(2): 32–40. https://doi.org/10.1080/14942119.2010.10702596.

ReVelle C.S., Eiselt H.A., Daskin M.S. (2008). A bibliography for some fundamental problem categories in discrete location science. European Journal of Operational Research 184(3): 817–848. https://doi.org/10.1016/j.ejor.2006.12.044.

Song G., Sun L. (2016). Evaluation of factors affecting strategic supply chain network design. International Journal of Logistics Research and Applications 20(5): 405–425. https://doi.org/10.1080/13675567.2016.1267125.

Suurs R. (2002). Long distance bioenergy logistics – an assessment of costs and energy consumption for various biomass energy transport chains. University of Utrecht. ISBN 90-73958-83-0.

Torno S., Knorz M., van de Kuilen J.-W. (2013). Supply of beech lamellas for the production of glued laminated timber. ISCHP 13 - International Scientific Conference on Hardwood Processing. p. 210–217.

Tran V.-D., Oudjene M., Méausoone P.J. (2016). Experimental investigation on full-scale glued oak solid timber beams for structural bearing capacity. Construction and Building Materials 123: 365–371. https://doi.org/10.1016/j.conbuildmat.2016.07.002.

Vila D., Martel A., Beauregard R. (2006). Designing logistics networks in divergent process industries: methodology and its application to the lumber industry. International Journal of Production Economics 102(2): 358–378. https://doi.org/10.1016/j.ijpe.2005.03.011.

Vögtli S. (2013). Industrielle Laubholz-Weiterverarbeitung in der Nordwestschweiz. Schlussbericht. [Industrial hardwood processing in northwest Switzerland (final report)]. Forestry associaction beider Basel. Verfügung Nr. 09.0063.PJ/4-13.02. https://www.bafu.admin.ch/dam/bafu/de/dokumente/wald-holz/fachinfo-daten/laubholzverarbeitungnordwestschweiz.pdf.download.pdf/laubholzverarbeitungnordwestschweiz.pdf. [Cited 9 August 2017]. [In German].

Walther G., Schatka A., Spengler T.S. (2012). Design of regional production networks for second generation synthetic bio-fuel – a case study in Northern Germany. European Journal of Operational Research 218(1): 280–292. https://doi.org/10.1016/j.ejor.2011.09.050.

Total of 39 references.

Paper IV

Kühle, S; Teischinger, A; Gronalt, M (2019c): Form-based postponement in the solid hardwood supply network. Cogent Business & Management. DOI: 10.1080/23311975.2019.1701887.

cogent business & management

MANAGEMENT | RESEARCH ARTICLE

Form-based postponement in the solid hardwood supply network

Sebastian Kühle, Alfred Teischinger and Manfred Gronalt

Cogent Business & Management (2019), 6: 1701887 cogent business & management

Received: 29 May 2019
Accepted: 04 December 2019
First Published: 24 December 2019

*Corresponding author: Sebastian Kühle, Institute of Wood Technology & Renewable Materials, University of Natural Resources and Applied Life Sciences Vienna (BOKU), Austria
E-mail: skuehle@boku.ac.at

Reviewing editor:
Len Tiu Wright, De Montfort University Faculty of Business and Law, UK

Additional information is available at the end of the article

MANAGEMENT | RESEARCH ARTICLE

Form-based postponement in the solid hardwood supply network

Sebastian Kühle[1]*, Alfred Teischinger[1] and Manfred Gronalt[2]

Abstract: For the foreseeable future the hardwood production network has an advantage due to the increasing availability of resources. The main challenge is to integrate the upcoming volume of raw material into the existing supply chain for sustainable value creation. This paper examines a form-based postponement concept in order to understand the balance between the benefits of increasing flexibility and the costs caused by it. The contribution of this paper is to apply a form postponement concept in the forest- and wood-based sector, especially the hardwood sector. This paper contains a process flow chart with additional production processes, parameters for material yields of the alternative production processes, an optimization model which calculates the lowest supply network cost and a case study with several network configurations. Results computed from the developed model and configurations show that there are several potentials for an enhanced flexibility of the supply network. On the one hand the combined processes lead to a higher material yield and on the other hand the specification of the product can be carried out later in production. This is made possible by the modularity of the products, by finishing processes at the end of the production unite and by the identification of more decoupling points.

ABOUT THE AUTHORS

Sebastian Kühle's research deals with multi-stage hardwood supply chains. The focus of this study deals with the technical production aspects and production capacities of the supply network in order to support strategic planning and network designs. It is a collaboration between the Institute of Wood Technology and Renewable Materials (IWT) with Prof. Teischinger and the Institute of Production and Logistics (IPL) with Prof.

Manfred Gronalt IWT researches the processing of renewable resources into sustainable materials and the hardwood topic is normally a subsection of research projects focused all types of wood. Their aim is to improve product utilisation using methods of material characterisation as well as product quality management and design.

IPL conducts problem and application-oriented research focusing on transport logistics for bioenergy and forestry, material flow design and production planning in the timber industry within the categories of optimization, simulation, risk analysis, benchmarking and performance indicators.

PUBLIC INTEREST STATEMENT

Currently, the utilization and value creation potential of hardwood is underestimated. Adaptations due to climate change results in an increase in the proportion of hardwood within forests and increasing hardwood stocks in central Europe. However, solid hardwood production capacities are already decreasing because of changes in the wood products market. There is a gap between the increasing importance of hardwood resources and the processing of the material along the supply chain with production units. One of the main challenges is to integrate the upcoming volume of raw material into existing supply chains for sustainable value-creation. The main contribution of this paper is the development of a future production concept using form postponement to close the gap between the increasing importance of hardwoods and the lack of production concepts within the solid hardwood supply network. This paper helps to analyse the impact on the production network if a form postponement concept is applied.

Subjects: Forestry; Operational Research / Management Science; Supply Chain Management; Forestry & Related Industries

Keywords: Postponement; supply network; beech wood; hardwood laminated wood product; flexibility; process flow; decoupling point

1. Introduction

In Europe, hardwood is becoming an increasing component of forests and this could benefit the hardwood production network.

Within this supply network, one of the main challenges is the integration of the growing volume of the raw material into existing production supply networks with their production facilities for sustainable value-creation. In the last two decades, the sub-sectors of industrial roundwood and fuelwood have steadily developed. This is not the case for the solid hardwood sector where individual and innovative utilization concepts are still absent. Market potential can be seen in laminated hardwood products for the construction industry (Luppold & Bumgardner, 2015).

Beech timber for glulam products has been investigated for over 20 years now with issues such as grading, finger joining and lamella connection. It has been shown that the suitability of beech wood as a laminated wood product is somewhat impaired by its durability and shrinkage (Breinig, Brüchert, Haas, & Sauter, 2015). Although it is technically possible to manufacture laminated beech wood products, there is a lack of research on the strategic planning of a solid hardwood supply network, especially within a network that is specialized in other product types. Currently, no company is constantly producing laminated hardwood products for the construction industry. Kühle, Teischinger, and Gronalt (2019) provided data to the solid hardwood business and develop a mixed-integer linear programming to design a laminated beech wood supply network.

For the flow of solid hardwood material, the sawmill is the focal element since it leads through production processes from sawing into a diverse material flow. Since material costs account for 40 – 70% of total costs, cutting patterns must match the demand of the final product. This has a major impact on total costs, material yield and revenue (Buehlmann, Edward Thomas, & Zuo, 2011; Torno, Knorz, & van de Kuilen, 2013).

There is a point in the process flow at which the manufacturer has to decide what to produce and for whom. To be more flexible and to have leverage within the supply network, a manufacturer should continue to analyse, adding this point to the existing knowledge. Within the hardwood sawmill, there are several decoupling points (DP) depending on products, production capacity and strategy. Either the procurement of raw material is already allocated to a customer order, or the primary and secondary log breakdown is allocated to a customer by using specific sawing patterns, also known as sawing policies (SP). Alternatively, this can also be undertaken during the edging and trimming of the dried board and herein lies potential which is supported in this paper. With two main product classes, furniture and construction, flexibility in production is necessary in order to satisfy order fulfilment, as well as maintaining low cost and high material yield.

It turns out that the potential lies in the use of the increased stock of hardwoods, which will continue to increase over the next decades and thus they gain even more importance. The challenge is to adapt supply networks and product concepts accordingly and to take into account the trend towards more customization within production planning. Postponement is a mass customization concept, which can close the gap.

We propose a postponement strategy within the hardwood sawmill which has an impact on the whole supply network. Consequently, the following section deals with the literature concerning the properties and benefits of postponement concepts as well as applied postponement concepts in the forest- and wood-based industry, especially the hardwood sector.

2. Literature review and preparatory work

The review of literature presents the properties of postponement and how this production management concept is used in the forestry- and wood-based sector. At the end of this section, the conclusions from the literature review and their significance for this paper will be presented in condensed form.

Postponement is used to reduce the potential uncertainty and to achieve flexibility in the product customization (Brun & Zorzini, 2009). It can be applied to move the DP closer to the customer. The DP is a boundary which specifies the position in the chain where the customization occurs. It distinguishes between forecast-driven operations in which future customer orders are anticipated and order-driven operations which are executed in the basis of customer orders (Hoek, 2001).

Companies use postponement to determine the DP in order to reduce customer lead time whilst permitting a degree of customization as well as to reduce the costs of the product and process variety (Iacocca & Liberatore, 2018; Trentin, Salvador, Forza, & Rungtusanatham, 2011). The concept affects inventory level as well as inventory cost, delivery lead time, supply chain flexibility and responsiveness all of which permits a quick reaction to changing customer needs, preferences and options (Saghiri, 2011).

For a company, there are two extremes of postponement: 1) the make-to-stock (MTS) which is suitable for high volume and low variety products and has the DP at the end of the process, and 2) the make-to-order (MTO) which is suitable for low volume and high variety products and has the DP at the beginning of the process. Production planning in a hybrid surrounding, like the production of intermediates for the construction and furniture market in the forest- and wood-based industry, is more challenging because both concepts have to be taken into account (Wilson, 2018).

Generally, postponement can be classified into three types: time, place and form postponement. Time postponement is the delaying of product movement for as long as possible within a physical distribution process which may support the minimization of costs and may maximize the responsiveness (Servare Junior, Cardoso, Cruz, & Paiva, 2018).

Place postponement is defined as maintaining the inventory at a centralized location and form postponement includes manufacturing, assembling, labelling and packaging postponement to finalize the product in response to customer orders (Bagchi & Gaur, 2018).

Further classifications of the postponement literature are presented in Hoek (2001).

For postponement, there are enablers which support the success of the implementation. For example, product modularity, component and process standardisation or process reorganization is seen as an enabler of postponement (Forza, Salvador, & Trentin, 2008; Saghiri, 2011).

Like Liu et al. (2014) and Al-Salim and Choobineh (2009) showed, there are several papers which methodically combine their research for the best DP in the process chain with an optimization model.

Harrison and Skipworth (2008) pointed out that form postponement can increase the flexibility of the production planning system but there is a gap between the theoretical perspective and practical implementation which has to be overcome. These gaps can be filled by the sectoral implementation of postponement.

For the forest- and wood-based sector it becomes clear that there has been a shift towards more customization and just-in-time deliveries as well as orders becoming smaller and more diverse (Espinoza, Buehlmann, Bumgardner, & Smith, 2014). Mass customization concepts support these shifts and have a positive impact on the domestic market strength of the sector (Lihra, Buehlmann, & Beauregard, 2008).

The following literature research shows that there are several papers that deal with a postponement in the forest- and wood-based industry and the advantages in application.

Audy et al. (2012) conducted an international case study in six different countries. Their main aim was to describe the wood supply chain and markets in order to assess their agility and tailoring capabilities. The focus was based on the forest activities. Two results are taken from the study for this paper: 1) the performance of tailoring is linked to the location of the DP and 2) the study identified two processes where most of the product differentiation activities (PDA) take place and concluded that the tailoring of a product specifications should take place before the PDA.

Nicholls and Bumgardner (2018) discussed the challenges and opportunities for North American hardwood manufacturers in using customization strategies with the related concepts of agility, lean manufacturing, economic clustering, and supply chain management. For the place postponement, the literature review found that imported components should be received as intermediates which are customized with features added at decentralized hubs closer to consumers.

Hauslmayer and Gronalt (2008) proposed a mass customization concept in the parquet industry for the production of wooden floorings. They implemented a time postponement. With this approach, they added more value to low-grade materials as well as reducing customer complaints about the final product defects.

Vendor-managed inventory (VMI), which involves time postponement but not necessarily place postponement, can reduce the overall raw material stock presented by Gronalt and Rauch (2008). Simultaneously, it increased the solid structure timber service level. In their research, the VMI was used to control the stock of sawn wood which is produced at a sawmill and delivered as raw material for solid structure timber production. With the VMI approach, it was possible to flatten demand deviations.

Alayet, Lehoux, and Lebel (2018) used postponement concepts with the goal of optimizing harvesting, storage, transportation, and production operations while improving the competitiveness of this proposed forest products supply chain. Postponement concepts are contained within MTS, MTO and VMI to optimize supply chain profit with a mathematical model. As in Gronalt and Rauch (2008), Alayet et al. (2018) showed that postponement strategies have a significant benefit for the user. For example, it provides the flexibility to adjust production to satisfy demand and VMI which leads to significant inventory cost reductions.

The literature review shows that there is potential for further postponement studies within the forest- and wood-based supply chains and that form postponement is not studied so far. Especially for postponement concepts in the solid hardwood supply network, there are no comprehensive case studies available. From the literature, it follows that the modularity of products must be taken into account, for example, through the use of standardized product components that can be assembled or standardized processes. An important step in the development of the postponement concept is the identification of DP along the supply chain. These points are decisions which have an influence on the downstream process and the customer's demand.

In this paper, the applied form postponement concept is introduced within sawmills. The DP is relocated from the roundwood procurement process to the sawmill or from the first cutting process to the second cutting process after the kiln-drying. The decision what to produce takes place after the drying process and with a different intermediate product: sawn wood instead of roundwood. This shift influences the delivery time and the downstream production processes. Thus, there is a time shift of four to 8 weeks to the customer depending on species and sawn board dimensions as well as a potential increase in material output.

The planning of the hardwood supply network is complex due to the extensive data used for the production network. Difficulties arise from the calculation of large amounts of data. Thus, the calculations of the supply network costs need a decision support (Drucker, 1995). Kühle et al. (2019) provided data of the solid hardwood production network and approaches for the mathematical model.

The research question in this paper is the following: Will the introduction of form postponement lead to lower supply network costs and increased use of resources?

The aim is to study the cost/benefit relationship of the chosen postponement policy and its impact on a potential solid hardwood production network.

The main contribution of this paper is the development of a future production concept using form postponement to close the gap between the increasing importance of hardwoods and the lack of production concepts within the solid hardwood supply network. Here, the appearance as well as the structural market are chosen with sawn beech timber and beech lamellas as intermediate products. Also, alternative process flows are presented with resulting yields of material and the chosen basic cutting patterns.

3. Material and methods

In order to create a flexible production concept with the lowest supply network costs which satisfies the demand of the two hardwood product markets, a process flow chart is firstly developed with additional production process flows. Secondly, the resulting material yields are determined for the alternative production flows. Thirdly, an optimization model is developed to calculate the lowest supply network cost from the forest departments to sawmills and then downstream manufacturers to the customer. Finally, the model is applied to the Austrian solid hardwood network as a case study with several varying network configurations.

3.1. The supply network considered

This paper considers the supply network which includes forest departments providing beech roundwood, hardwood sawmills which distribute the material flow either to the laminated beech wood facilities (LBWF) or to the furniture market and finally customer using laminated beech products (Figure 1).

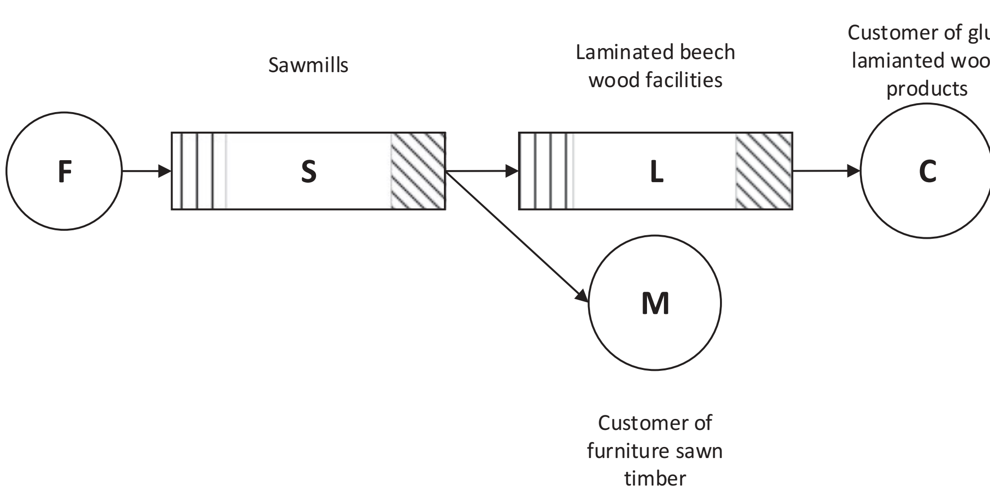


Figure 1. The model of a solid hardwood supply network is presented with its stakeholders and the material flows between them. There is a direct flow from one entity to all entities in the next tier. The source is the forest department and the sink is the customer of either laminated wood products or for furniture sawn timber.

3.2. Process flow

3.2.1. Material flows

The process flow chart represents three main production process flows and connects the decisions which result in diverse material flows and different material yields (Figure 2).

The standard process flows consist of either the production of lamellas for glued timber products as an intermediate or of the sawn timber for furniture products (#0). A third process flow is added. It represents the production of glued lamellas out of a single-layer panel. The concept is developed by Ressel (2002) and is also considered by Hönnebeck (2008).

Within the process flow chart, there are two kinds of decisions. One is a general decision of the material flow and the other is related to the quality of the input material. The general decision assumes that sawmill owners try to satisfy the demand of lamellas more than the demand of sawn timber for furniture products. 60.0% of intermediates flow into the lamella production after the kiln-drying and 40.0% into sawn timber (#1).

There are three decisions which are related to the quality of the input material and they decide if a specific input material is suitable for the next process step, which adds value to the product or not.

The strength sorting is based on standards which divide the material flow into lamellas which are suitable for laminated timber products and which are not. The latter flows into the sawn timber process chain for furniture products (#2).

Within the production of sawn timber, there is a decision which determines whether the input material is suitable for the sawn timber intermediate or not. If yes, then the sawn timber is completed and stored and if it does not fulfil the quality requirements, then it goes into the production process of the single-layer panel (#3).

The last decision determines if the input material is suitable for the production of a single-layer panel. If the decision is positive, the material goes into production. Otherwise, the material is not considered in this paper (#4).

3.2.2. Calculation of the relative material yield

Different material yields result from the process flows developed. They are integrated into the optimization model with several cutting patterns to choose from. The calculations of the material yields are the basis for the subsequent numerical experiment.

An initial proportion of 64.0% is assumed which results after the drying process (Table 1). From this initial amount 60.0% are dedicated to the production of lamellas and 40.0% to sawn timber. Thus, there is a first mixed outcome with 21.5% of lamellas and 17.9% of sawn timber as the final product of the hardwood sawmill. From the decision #3, there is an additional amount of 5.1% for the sawn timber. Finally, from the decision #4, 8.2% of material flow into lamellas. Besides the additional material flows, there is the possibility to only choose either the production of lamellas with 22.0% or sawn timber with 40.0 %. A compilation of the values is presented in Table 2.

The additional production processes that are responsible for a potential increase in yields also generate additional costs. The additional costs were determined according to the relative cost expenditure as presented in Table 3 according to the SP. In Table 4 the additional costs are presented alongside the variable sawing cost. The result is a cost span with a minimum and maximum value (Table 4).

cogent • business & management

Figure 2. The process flow chart shows the three main production processes with lamellas (right), sawn timber (middle) and single-layer panel (left). They are connected by four decisions elements which are marked with numbers. At the left, the position of the decoupling point is presented between forecast driven and order driven. Also, the types of decisions are represented with #1 the general decision and #2, #3 and #4 the postponement decisions.

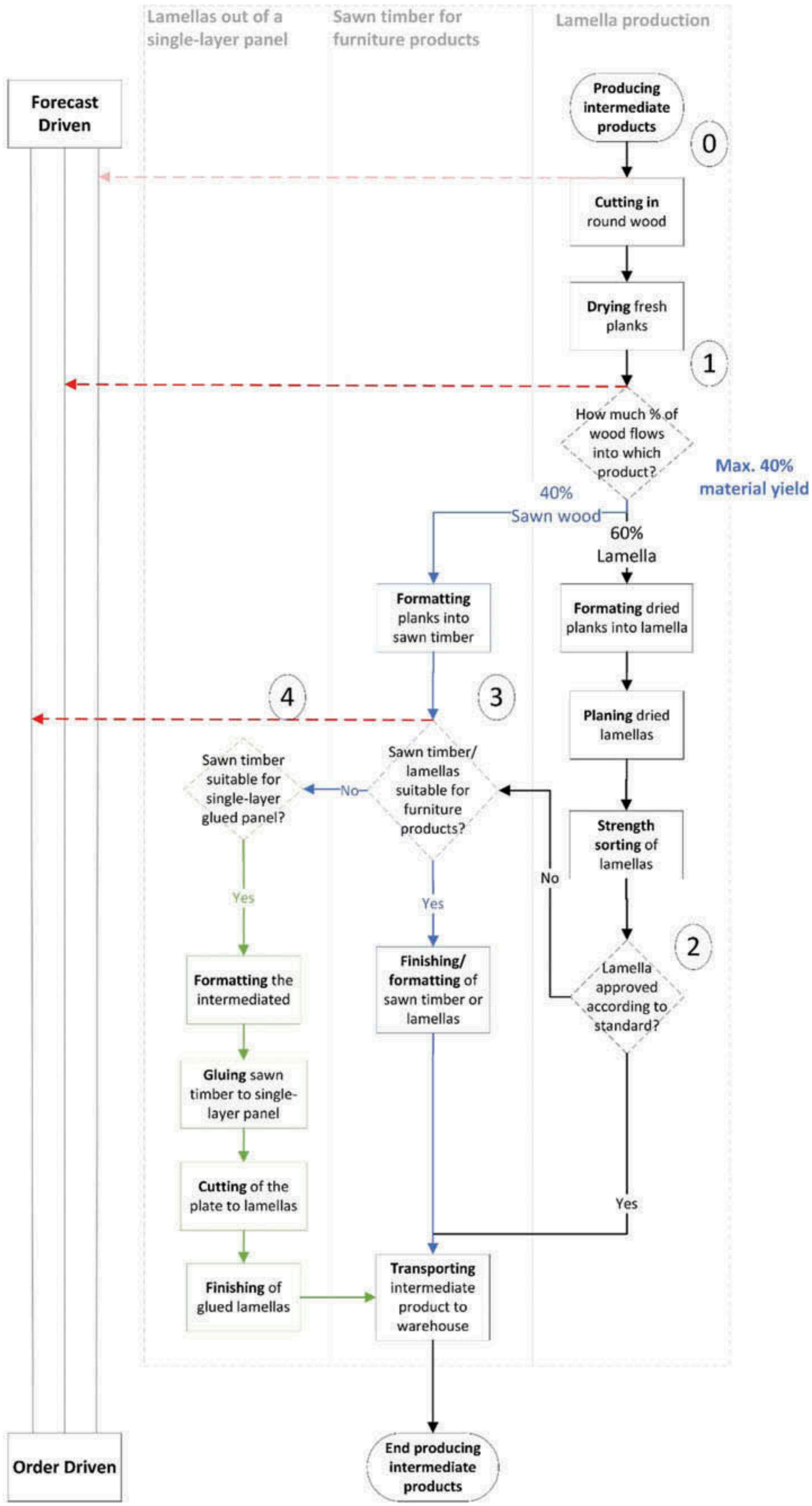


Table 1. Calculated material yields for the two different final products by considering the additional production process flows. The four decisions from the process chart are shown as well as the resulting relative material yields, which are added to the quantity of the end-product

		Lamellas for laminated timber [%]	Sawn timber for furniture products [%]
	Relative amount of input material after the drying process	64.0	
#1	Chosen distribution for the raw material	60.0	40.0
#2	Standard mixed outcome		
	Raw material	38.4	25.6
	By-products distribution	44.0	30.0
	By-products	16.9	7.7
	+ sawmill products	**21.5**	**17.9**
#3	Alternative utilisation of out sorted lamellas for sawn timber		
	Utilisation of by-products	30.0	
	+ for sawn timber	**5.1**	
#4	Utilisation of out sorted sawn timber for single-layer panel		
	Utilisation of by-products	30.0	40.0
	+ for lamellar	**5.1**	**3.1**

Table 2. The final material outputs resulting from the additional process decisions and SP are displayed. They are printed in bold for the individual SP

	Process 1		Process 2		Process 3	
Sawing policy	**Lamella [%]**	**Sawn timber [%]**	**Lamella [%]**	**Sawn timber [%]**	**Sorted out lamellas for furniture sawn timber [%]**	**Single-layer panel for the manufacture of lamellas [%]**
1.1	**22.0** (100%)	**0.0**				
1.2	**0.0**	**40.0** (100%)				
2	38.4 (60%)	25.6 (40%)	**21.5**	**17.9**		
3	38.4 (60%)	25.6 (40%)	**21.5**	17.9	**23.0** (+ 5.1)	
4	38.4 (60%)	25.6 (40%)	21.5	17.9	**23.0** (+ 5.1)	**29.7** (+ 8.2)

3.3. Model description

We propose a linear programming model to find the minimal cost for the supply network which fulfils a specific demand of two product markets per year. The model considers several parameters which characterize the following five entities: forest departments, sawmills, LBWF, buyer of beech sawn wood for furniture and laminated beech wood market.

Decision variables are introduced to describe material flows in these entities and within the solid hardwood supply network.

Table 3. Material yield and additional cost for the individual SP. For each SP, the material yields for lamellas (product 1) and sawn timber (product 2) are presented in %. From SP 1, the basis policy, the following policies are developed. There are relative cost expenditures for SP 3 and 4

Sawing policy	Material yield for product 1 and 2 [%]	Relative cost expenditures [%]
1	0.220 0.0; 0.0 0.400	0
2	0.220 0.0; 0.215 0.179; 0.0 0.400;	0
3	0.220 0.0; 0.0 0.400; 0.215 0.230;	+10
4	0.220 0.0; 0.0 0.400; 0.297 0.230;	+35

Table 4. Additional expenditures of the alternative production processes are presented depending on the sawmill production capacity in %. This results into a cost span which is shown with min and max values

Sawing policy	Sawmill capacity [m^3 of roundwood]	Cutting cost [€/m^3 roundwood]		Additional cost [€/m^3 roundwood]
1 and 2	> 45 000 (+0%)	30.00	Min	+0.00
	< 20 000 (+0%)	48.00	Max	+0.00
3	> 45 000 (+10%)	30.00	Min	+3.00
	< 20 000 (+10%)	48.00	Max	+4.80
4	> 45 000 (+35%)	30.00	Min	+10.50
	< 20 000 (+35%)	48.00	Max	+16.80

The following section presents the exact formulation of the optimization model, defining sets, the objective function, decision variables and constraints.

Indices

F	Set of forest departments
S	Set of sawmills
L	Set of laminated beech wood facility
M	Set of customers for furniture sawn timber
C	Set of customers for laminated beech wood products
P	Set of products
A	Set of sawing policy
T	Set of periods

Parameter

C_{fs}^{trans}	Transportation distance from forest f to sawmill s in km
C_{sl}^{trans}	Transportation distance from sawmill s to LBWF l in km
C_{sm}^{trans}	Transportation distance from sawmill s to customer of furniture sawn timber m in km
C_{lc}^{trans}	Transportation distance from LBWF l to customer c in km
C_{s}^{prodS}	Unit sawing cost at sawmill s in €/m³

C^{prodL}	Unit sawing cost at LBWF in €/m³
CAP_{tf}	Amount of resource at forest location f in period t in m³ of roundwood
CAP_{st}	Production capacity at sawmill s in period t in m³
CAP_{lpt}	Production capacity at LBWF l for product p in period t in m³
S_p^{invSR}	Start inventory of raw material p at sawmill in m³ of roundwood
S_p^{invSP}	Start inventory of product p at sawmill in m³
S_p^{invLR}	Start inventory of raw material p at LBWF m³
S_p^{invLP}	Start inventory of product p at LBWF m³
C_p^{invSR}	Unit inventory cost for raw material p at sawmill in €/m³
C_p^{invSP}	Unit inventory cost for product p at sawmill in €/m³
C_p^{invLR}	Unit inventory cost for raw material p at LBWF in €/m³
C_p^{invLP}	Unit inventory cost for product p at LBWF in €/m³
D_{cpt}	Demand of laminated beech wood product p from customer c in period t in m³
D_{mpt}	Demand of furniture sawn timber p from customer m in period t in m³
C_1, C_2, C_3	Transport cost coefficient in €/m³km
$alpha_{ap}$	proportion of intermediate product p produced when applying sawing policy a
η	Material yield at LBWF
C^{mat}	Unit procurement cost of raw material in €
B, M	High values

Variables

x_{fst}	Amount of roundwood shipped from forest f to sawmill s in period t in m³ of roundwood
x_{smpt}	Amount of sawn timber p shipped from sawmill s to customer m in period t in m³
x_{slpt}	Amount of lamella p shipped from sawmill s to LBWF l in period t in m³
x_{lcpt}	Amount of product p shipped from LBWF l to customer c in period t m³
p_{ast}	Amount of consumed roundwood at sawmill s wit sawing policy a in period t in m³ of roundwood
p_{lpt}	Amount of consumed lamella p at LBWF l in period t in m³
i_{st}^{invSR}	Inventory level of raw material at sawmill s in period t in m³ of roundwood
i_{spt}^{invSP}	Inventory level of product p at sawmill s in period t in m³
i_{lpt}^{invLR}	Inventory level of raw material p at LBWF l in period t m³
i_{lpt}^{invLP}	Inventory level of product p at LBWF l in period t m³
u_{cpt}	Unsatisfied demand of laminated beech wood product p at customer c in period t in m³
u_{mpt}	Unsatisfied demand of sawn timber product p at customer c in period t in m³

3.3.1. Objective function

The objective function is to minimize the total cost of the supply network. The costs of the model comprise transportation, sawing at the sawmills, production at the LBWF, inventory at the sawmills and the LBWF, roundwood procurement and demand shortage (1).

$$\min(z) = \sum_{t\epsilon T, f\epsilon F, s\epsilon S} C_1 * C^{trans}_{fs} * x_{fst} + \sum_{s\epsilon S, m\epsilon M, p\epsilon P, t\epsilon T} C_2 * C^{trans}_{sm} * x_{smpt} + \sum_{s\epsilon S, l\epsilon L, p\epsilon P, t\epsilon T} C_2 * C^{trans}_{sl} * x_{slpt}$$
$$+ \sum_{s\epsilon S, l\epsilon L, p\epsilon P, t\epsilon T} C_3 * C^{trans}_{lc} * x_{lcpt} + \sum_{a\epsilon A, s\epsilon S, t\epsilon T} C^{prodS}_{s} * p_{ast} + \sum_{l\epsilon L, p\epsilon P, t\epsilon T} C^{prodL} * p_{lpt}$$
$$+ \sum_{t\epsilon T, s\epsilon S} C^{invSR}_{p} * i^{invSR}_{st} + \sum_{s\epsilon S, p\epsilon P, t\epsilon T} C^{invSP}_{p} * i^{invSL}_{spt} + \sum_{l\epsilon L, p\epsilon P, t\epsilon T} C^{invLR}_{p} * i^{invLR}_{lpt} + \sum_{l\epsilon L, p\epsilon P, t\epsilon T} C^{invLP}_{p} * i^{invLP}_{lpt}$$
$$+ \sum_{f\epsilon F, s\epsilon S, t\epsilon T} C^{mat} * x_{fst} + \sum_{c\epsilon C, p\epsilon P, t\epsilon T,} B * u_{cpt} + \sum_{m\epsilon M, p\epsilon P, t\epsilon T} M * u_{mpt} \tag{1}$$

The decision variables u_{cpt} and u_{mpt} are used to guarantee maximal demand satisfaction up to specific network cost. There will be model configurations which do not satisfy the demand constraint thus a model objective value of 0 will be provided. To counteract this effect, the decision variables are introduced thus also a not fully achieved demand satisfaction will provide a solution.

3.3.2. Constraints

Constraints (2–4) are introduced as parameters for the material flow equalization Equations (2) represents the used roundwood, (3) the produced intermediate products at the sawmill and (4) the final laminated beech wood product. It is to highlight this that time shifts have been introduced to reflect general production and delivery times. Within the sawmills (3), there is a time shift of *t + 2* and within the LBWF *t + 1* (4).

Constraints (5–7) provide the production and supply capacity constraint for forest departments, sawmills and LBWF.

Constraints (7), (9), (11) and (13) represent the inventory levels for the periods higher than one, while every other constraint represents the inventory level for the first periods. Thus, the start inventory S^{inv}_{p} is introduced.

Constraint (15–16) defines the demand satisfaction constraints stating that the determined demand is every time-satisfied by the sum of the product shipment and the unsatisfied demand variable. Finally, variables are defined as non-negativity (17).

$$con_{st} := \sum_{a\epsilon A} p_{ast} \qquad \forall\, s\,\epsilon\, S,\ t\,\epsilon\, T \tag{2}$$

$$pro_{sp(t+2)} := \sum_{a\epsilon A} alpha_{ap} * p_{ast} \quad \forall\, l\,\epsilon\, L,\ p\,\epsilon\, P,\ t\,\epsilon\, T \tag{3}$$

$$ass_{lp(t+1)} := \eta * p_{lpt} \quad \forall\, l\,\epsilon\, L,\ p\,\epsilon\, P,\ t\,\epsilon\, T \tag{4}$$

$$\sum_{s\epsilon S} x_{fst} \leq CAP_{ft} \quad \forall\, f\,\epsilon\, F,\ t\,\epsilon\, T \tag{5}$$

$$\sum_{a\epsilon A} p_{ast} \leq CAP_{st} \quad \forall\, s\,\epsilon\, S,\ t\,\epsilon\, T \tag{6}$$

$$i^{invSR}_{st} = i^{invSR}_{s(t-1)} + \sum_{f\in F} x_{fst} - con_{st} \forall\, s\,\epsilon\, S,\ t\,\epsilon\, T\,|\,t>1 \tag{7}$$

$$i^{invSR}_{st} = S^{invSR}_{p} + \sum_{f\epsilon F} x_{fst} - con_{st} \quad \forall\, s\,\epsilon\, S,\ t\,\epsilon\, T\,|\,t=1 \tag{8}$$

$$i^{invSP}_{spt} = i^{invSP}_{sp(t-1)} + pro_{spt} - \sum_{m\epsilon M} x_{smpt} - \sum_{l\epsilon L} x_{slpt} \quad \forall\, s\,\epsilon\, S,\ p\,\epsilon\, P,\ t\,\epsilon\, T\,|\,t>1 \tag{9}$$

$$i_{spt}^{invSP} = S_p^{invSP} + pro_{spt} - \sum_{m \epsilon M} x_{smpt} - \sum_{l \epsilon L} x_{slpt} \quad \forall\, s \,\epsilon\, S,\ p \,\epsilon\, P,\ t \,\epsilon\, T \,|\, t = 1 \tag{10}$$

$$i_{lpt}^{invLR} = i_{lp(t-1)}^{invLR} + \sum_{s \in S} x_{slpt} - p_{lplt} \quad \forall\, l \,\epsilon\, L,\ p \,\epsilon\, P,\ t \,\epsilon\, T \,|\, t > 1 \tag{11}$$

$$i_{lpt}^{invLR} = S_p^{invLR} + \sum_{s \epsilon S} x_{slpt} - p_{lplt} \quad \forall\, l \,\epsilon\, L,\ p \,\epsilon\, P,\ t \,\epsilon\, T \,|\, t = 1 \tag{12}$$

$$i_{lpt}^{invLP} = i_{lp(t-1)}^{invLP} + ass_{lpt} - \sum_{c \epsilon C} x_{lcpt} \quad \forall\, l \,\epsilon\, L,\ p \,\epsilon\, P,\ t \,\epsilon\, T \,|\, t > 1 \tag{13}$$

$$i_{lpt}^{invLP} = S_p^{invLP} + ass_{lpt} - \sum_{c \epsilon C} x_{lcpt} \quad \forall\, l \,\epsilon\, L,\ p \,\epsilon\, P,\ t \,\epsilon\, T \,|\, t = 1 \tag{14}$$

$$\sum_{l \epsilon L} x_{lcpt} + u_{cpt} = D_{cpt} \quad \forall, c \epsilon C, p \epsilon P, t \epsilon T \tag{15}$$

$$\sum_{s \epsilon S} x_{smpt} + u_{mpt} = D_{mpt} \quad \forall, m \epsilon M, p \epsilon P, t \epsilon T \tag{16}$$

$$i_{ts}^{invR}, i_{ts}^{invL}, i_{tl}^{invI}, i_{tl}^{invB}, x_{tfs}, x_{tsl}, x_{tlc}, p_{ts}, p_{tl}, u_{tc} \geq 0 \tag{17}$$

3.3.3. Numerical experiments and scenario setup

Five supply network configurations are developed in order to test the sensitivity and to evaluate the resulting network cost for each of the configurations. In the following, supply network configurations are referred to as scenarios.

The first scenarios (S1) represents a national sourcing strategy and a national customer demand which is satisfied by two LBWF. For the second scenarios (S2), the sourcing strategy changes from national to transnational with resources from bordering countries. Scenario three (S3) is used in order to examine the supply of laminated beech wood production from only one location. All other parameters are the same as in the second scenario. In additionally to S3, a transnational demand is defined for the fourth scenario (S4). After the expansion of the demand in S4, two LBWF locations are implemented for the fifth scenario (S5) in order to examine the impact of the distribution of the production locations.

In addition to the five given network configurations, the specific sawing policies are calculated in individual scenarios. The material yields for each policy are used from Table 3 as well as the additional costs from Table 4. Policy #1 can only meet customer demand for product 1 or 2, as the policy is applied to only one. Instead of calculating these individually, they are integrated into saw policies #2, #3, and #4.

With the supply network configurations and saw policies, 15 scenarios are calculated in total.

3.3.4. Performance measurement

To report information regarding the performance of the considered supply network configurations, the total costs of the individual scenarios are presented in €/m^3 and compared in combination with the sawing policies used ($totalcost_{alpha,scenario}$), which are a result of the developed production processes to achieve a more flexible supply network. A matrix (Table 7) will represent the savings or decreases of cost with *rel*Δ *total* cost in % for the comparison:

$$rel\ \Delta\ total\ cost_{21-22} = \frac{total\ cost_{21} - total\ cost_{22}}{total\ cost_{22}} * 100\% \tag{18}$$

The calculated cost differences are compared to the costs emerging from the supplementary production process $supcost_{alpha}$(Equation 20). Therefore, the mean value of all computed total cost is used (Equation 19).

$$\overline{total\ cost}_{alpha,scenario} = \frac{1}{n}\sum_{i=1}^{n} total\ cost_{alpha,scenario} \tag{19}$$

$$rel\ sup\ cost_{alpha} = \frac{sup\ cost_{alpha}}{\overline{total\ cost}_{alpha,scenario}} * 100\% \tag{20}$$

The degree of satisfied demand for laminated as well as sawn beech timber products, the amount of resources used, the level of imported resources, the utilisation of sawmill capacity and the level of facility capacity used are presented in %.

4. Results

The material performances are shown in Table 5 for the computed supply network configurations. The objective of a production supply network is to fulfil the demand of the customers with specific constraints. In this model, the demand of two different markets must be satisfied. For almost all SP and scenario combinations, the demand has been met for sawn beech timber (DF ST). The highest demand of laminated beech wood products has been met with 73.0% with SP 4 (DF GLP).

Only 68.0% of the available resources are used with the national sourcing strategy of S1 (A UR). With the transnational resource locations, low amounts are used which is represented by the low value for used resources and the low value of imported resources (A IR) for S2—S5.

No more than 52.0% of the sawmill capacity was used (A USC). For LBWF, the capacity was almost fully utilized for the network constellation with only one of them used (A UFC). With SP 4, the constellation with two facilities are almost completely utilized.

Table 6 represents the total cost for the SP in combination with the five scenarios. The lowest total cost is calculated for S1 in combination with SP 4. If only the SP are considered, then the lowest costs are calculated for SP 4 for the first three scenarios and for SP 2 for the last two. The scenarios with only one LBWF always have costs higher than the equal scenario settings with two facilities. Considering the scenarios and the highest total cost, S3 and S4 have a value higher than S5 with the transnational demand.

The flexibility of the production processes has an impact on the cost. By way of an illustration, there is an increase of 10.0% on the production cost resulting from the adaption of process for SP 3

Table 5. Material performance results of the chosen SP 2, 3 and 4 as well as scenarios 1 to 5 are presented in %

Parameter	Sawing policy														
	2 [%]					3 [%]					4 [%]				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
DF GLP	23	31	22	20	26	38	55	37	36	54	61	73	39	39	73
DF ST	100	100	100	100	100	96	100	100	100	100	84	100	100	100	100
A UR	68	34	29	29	34	68	34	29	29	34	68	34	27	27	34
A IR	0	8	4	4	8	0	8	4	4	8	0	9	4	4	9
A USC	44	52	46	45	51	44	52	46	45	51	44	52	43	43	52
A UFC	47	69	93	91	67	47	69	93	91	67	76	91	97	97	91

Table 6. Total cost of the chosen SP and scenarios are presented

Sawing policy	Scenarios [€]				
	S1	**S2**	**S3**	**S4**	**S5**
2	306	311	313	314	309
3	304	312	318	320	317
4	292	302	313	316	310

Table 7. Here the relative-reduced costs per m³ compared to the SP values are alongside the relative additional costs

Comparison of sawing policies	*rel∆totalcost* **[%]**					*relsupcost*[%]	
	S1	**S2**	**S3**	**S4**	**S5**	**Min**	**Max**
3 & 2	−0.6	0.6	1.3	2.0%	2.5	1.0	1.5
4 & 2	−4.6	−2.6	−0.2	0.8%	0.2	3.4	5.4
4 & 3	−4.0	−3.2	−1.5	−1.2%	−2.3	3.4	5.4

and an increase of 35.0% for SP 4. The cost range of the production costs in the sawmill is divided by the mean *total cost*.

This results in a relative cost increase for SP 3 of 1.0% to 1.5% and for SP 4 of 3.4% to 5.4% (Table 7). In order to balance costs and savings, the relative values should lie within the respective ranges. A higher value means more savings than costs.

The comparison of SP 3 and 2 shows that one value lies within the range (S3) and two values lie above it with the scenarios S4 and S5. The comparison of SP 4 to 2 and 3 shows that only one value lies within the range, which is the value for the S1.

5. Discussion

This paper discusses the use of form postponement for the forest- and wood-based sector. The results show that there are influences on the total cost of the production network when applying the defined scenarios of form postponement. In the following, the results are generally discussed with regard to the postponement concept and then for the application to the specific industrial sector with regard to the effects on the costs and on the material flows.

5.1 General discussion of the form postponement

The form postponement involves the delay of activities that determine the form and function of products. This makes it necessary to adapt product processes or product components such as dimensions. This is also true for this research work, as Figure 2 shows where these adjustments and changes occur.

Similar to Van Kampen and Van Donk (2014), the implementation of form postponement is only within a single location. The literature shows that if several production units were needed to implement the postponement concept, then the process costs for all involved would increase and the knowledge about quality and quality fulfilment would decrease, since several production sites are involved and a higher exchange of information is needed. In order to reduce the previous negative effects, we would also recommend the implementation of form postponement within one production site.

In this paper, it can be seen that form postponement occurs within a single production unit. This is possible, for example, by further process chains in the process flow chart (Figure 2) by combining the production of product components for construction and furniture sawn wood. In turn, this is only possible due to the modularity of the products, material and dimensions. The literature refers to product and process modularity as an enabler for form postponement (Forza et al., 2008). This change in the production chain has an impact on the downstream. Here it is on the material yield as well as on the entire supply network cost (tables 2 and 7).

A common advantage of postponement in the literature is seen in the reduction of uncertainty (Hoek, 2001). This statement cannot be answered directly in this paper. What can be said from the results and the process flow chart is that, on the one hand, the combined processes lead to a higher material yield and, on the other hand, the specification of the product can be carried out later in production. This is possible by the modularity of the products, by finishing processes at the end of the production chain in the sawmill and by the possibility to make decisions to produce certain products in the production by increased DP. For the supply network and the fulfilment of customer requirements, this could lead to greater flexibility and possibly to shorter delivery times.

5.2 Specific findings in form postponement for the forest- and wood-based sector especially on the used case study

For the chosen framework, the results show that the demand for sawn beech timber in furniture production continues to exist within the given sawmill production capacities and is fully met in most cases. For laminated beech wood products, no complete demand fulfilment is possible, as the production capacities of the LBWF are almost completely used.

The results of the SP 4 scenario show that new cutting patterns have to be developed in order to fit the product process portfolio along the supply chain and for individual companies (Abasian, Rönnqvist, & Ouhimmou, 2017). The individual total cost comparison of SP4 to the variants of SP 2 and 3 shows that cost reductions are possible there (Table 7). The result suggests that it is more likely to buy raw materials nationally and satisfy customer demands, as S1's cost reductions are the highest in comparison to the other scenarios. Here it must be pointed out that the scenario serves the lowest demand of the absolute quantity. Delivery transport costs have an important role to play here. It must be taken into account that with an increased demand, the distances to the individual customers also increase and thus the transport costs also rise proportionately. This is especially true when roundwood is procured abroad and derived from distant locations. The same applies to end products. This effect can also be seen in Kühle et al. (2019). They give literature recommendations, which deal more specifically with this challenge and with further challenges in the hardwood production network.

For strategic planning of the supply network, the form postponement developed here and the linked adoptions of production processes have the advantage that they lead to an increased material utilization. On the supply side, this leads to a decreased need to purchase raw materials within the supply network and to an increased satisfaction of demand on the customer side. This is shown by the increases in the higher utilisation of capacity in further processing and the constant capacity in the sawmill (Table 5). Both could lead to clear financial advantages, which would need to be considered more closely in tactical planning and operational execution. There is still potential for further work to move from strategic planning to a day-to-day implementation.

In addition, it can be emphasized that the third main process, leading to the production of a single-layer board, can be used not only for the production of lamellas but also for single-layer furniture boards for which there is already a market.

Within the solid hardwood production network, the greatest challenges arise for sawmills. The production processes leading to a diverse flow of material also results in the most changes.

cogent • business & management

However, this paper also shows that there are several decision-making options leading to a further room for action. In addition to retaining the existing products, it is possible to switch completely to new products, to stay with the known products or to use a mixed form (Table 1). For the latter, this paper shows that with the help of the production processes developed, further points in the process flow arise at which the production of an intermediate can be decided. This gives the producer more flexibility in satisfying demand.

6. Conclusion

A form postponement strategy is developed and determined in order to add flexibility to the supply of products for two different markets in the solid hardwood production network. For this purpose, production processes were developed and presented, which also result in new material yields.

The contribution of this paper is to apply a form postponement concept in the forest- and wood-based sector, especially the hardwood sector. It turns out that the application of form postponement to a specific production sector is challenging and complex. Further research is needed in this area to translate theory into practice.

The research question of whether form postponement leads to lower supply network costs while simultaneously increasing material utilization cannot be clearly substantiated. The extension of the production processes to generate an increased material yield also generates additional costs. These costs are in some cases lower and in some cases higher than the savings from the lower purchase of raw materials and the revenues of higher satisfaction of customer demands. In practical application, these costs must be compared with the benefits, such as shorter delivery times and the possibility to fulfil customer requests more flexibly (Waller, Dabholkar, & Gentry, 2000). When deciding on the postponement, companies are faced with an increase in production costs and an increase in expected revenues due to a better estimate of demand. Therefore, it is important for companies to find the optimal balance between costs and benefits achieved by the postponement process (Bagchi & Gaur, 2018).

Finally, the challenges mentioned in the paper, which arise during the conversion of production processes and the application of the form postponement concept, can be overcome at an early stage by means of change management. This change management is mentioned as the single most critical success factor during such major adaptions of processes (Hoek, 2001). For the hardwood supply network, factors which support this change process are, among others, more administration and planning skills to adapt to fast-changing production requirements, powerful, flexible, and user-friendly information technology and the increase of labour skills such as the degree of technical competences and flexibility (Lihra et al., 2008).

Acknowledgements
Financial support for this work in the framework of the PhD School DokIn´Holz funded by the Austrian Federal Ministry of Science, Research and Economy as well as the Austrian Federal Forestry Office and the Austrian Chamber of Agriculture are gratefully acknowledged. The open access publication was supported by BOKU Vienna Open Access Publishing Fund.

Author details
Sebastian Kühle[1]
E-mail: skuehle@boku.ac.at
ORCID ID: http://orcid.org/0000-0003-0628-5038
Alfred Teischinger[1]
E-mail: alfred.teischinger@boku.ac.at
Manfred Gronalt[2]
E-mail: manfred.gronalt@boku.ac.at
ORCID ID: http://orcid.org/0000-0003-0944-4911
[1] Department of Material Science and Process Engineering, and Renewable Institute of Wood Technology Materials, BOKU - University of Natural Resources and Life Sciences, Vienna, Konrad-Lorenz-Straße 24, Tulln 3430, Austria.
[2] Department of Economics and Social Sciences, Institute of Production and Logistics, BOKU - University of Natural Resources and Life Sciences, Vienna, Feistmantelstraße 4, Vienna 1180, Austria.

Cover Image
Source: Author.

Citation information
Cite this article as: Form-based postponement in the solid hardwood supply network, Sebastian Kühle, Alfred Teischinger & Manfred Gronalt, *Cogent Business & Management* (2019), 6: 1701887.

References

Abasian, F., Rönnqvist, M., & Ouhimmou, M. (2017). Forest fibre network design with multiple assortments: A case study in Newfoundland. *Canadian Journal of Forest Research*, 47. doi:10.1139/cjfr-2016-0504

Alayet, C., Lehoux, N., & Lebel, L. (2018). Logistics approaches assessment to better coordinate a forest products supply chain. *Journal of Forest Economics*, *30*, 13–24. doi:10.1016/j.jfe.2017.11.001

Al-Salim, A., & Choobineh, F. (2009). Redesign of production flow lines to postpone product differentiation. *International Journal of Production Research*, *47*(20), 5563–5590. doi:10.1080/00207540802154837

Audy,Québec, J. F., Moreira, M., Westlund, K., D'Amours, S., Lebel, L., & Rönnqvist, M. (2012). Alternative logistics concepts fitting different wood supply situations and markets. In *CIRRELT research report*.

Bagchi, S. S., & Gaur, J. (2018). Optimization of postponement process for a two stage modular manufacturer. *In Journal of Global Operations and Strategic Sourcing*, *11*(1), 39–54. doi:10.1108/JGOSS-03-2017-0009

Breinig, L., Brüchert, F., Haas, A., & Sauter, U. (2015). Evaluation of European beech (Fagus sylvatica L.) roundwood for improved production of strength-graded lamellas. *In Conference: 5th International Scientific Conference on Hardwood Processing*. Quebec City.

Brun, A., & Zorzini, M. (2009). Evaluation of product customization strategies through modularization and postponement. *International Journal of Production Economics*, *120*(1), 205–220. doi:10.1016/j.ijpe.2008.07.020

Buehlmann, U., Edward Thomas, R., & Zuo, X. (2011). Cost minimization through optimized raw material quality composition. In *Robotics and computer-integrated manufacturing - ROBOT COMPUT-INTEGR MANUF*. Vol. 27. doi: 10.1016/j.rcim.2010.12.013

Drucker, P. F. (1995). The information executives truly need. *Harvard Business Review*(pp. 9). January–February 1995..

Espinoza, O., Buehlmann, U., Bumgardner, M., & Smith, R. (2014). Intermediaries in the U.S. hardwood lumber market: Comparing and contrasting sawmills and distributors. *BioResources*, *9*, 6527–6539. doi:10.15376/biores.9.4.6527-6539

Forza, C., Salvador, F., & Trentin, A. (2008). Form postponement effects on operational performance: A typological theory. *International Journal of Operations & Production Management*, *28*(11), 1067–1094. doi:10.1108/01443570810910197

Gronalt, M., & Rauch, P. (2008). Vendor managed inventory in wood processing industries - A case study. *Silva Fennica*, *42*, 101–114. doi:10.14214/sf.267

Harrison, A., & Skipworth, H. (2008). Implications of form postponement to manufacturing: A cross case comparison. *International Journal of Production Research*, *46*(1), 173–195. doi:10.1080/00207540600844076

Hauslmayer, H., & Gronalt, M. (2008). Mass customisation in the woodworking industry – A simulation study for the parquet flooring industry. *International Journal of Mass Customisation*, *2*, 179. doi:10.1504/IJMASSC.2008.017139

Hoek, R. (2001). The rediscovery of postponement a literature review and directions for research. *Journal of Operations Management*, *19*, 161–184. doi:10.1016/S0272-6963(00)00057-7

Hönnebeck, J. (2008). *Untersuchungen zur Herstellung kostengünstiger Brettlamellenaus Buchenholz für Brettschichtholz* [Investigations into the production of low-cost lamellas made of beech wood for glued laminated timber]. Diploma, Munich, Technische Universität München, Holzforschung München.

Iacocca, K., & Liberatore, M. (2018). An empirical study of service postponement. Locating the push–Pull boundary. *International Journal of Production Research*, *56*(12), 4100–4114. doi:10.1080/00207543.2018.1436786

Kühle, S., Teischinger, A., & Gronalt, M. (2019). Optimal location of laminated beech production plants within the solid hardwood supply network in Austria. *Silva Fennica*, *53*, 3. doi:10.14214/sf.10074

Lihra, T., Buehlmann, U., & Beauregard, R. (2008). Mass customisation of wood furniture as a competitive strategy. *IJMASSC*, *2*(3/4), 200. doi:10.1504/IJMASSC.2008.017140

Liu, W., Mo, Y., Yang, Y., & Ye, Z. (2014). Decision model of customer order decoupling point on multiple customer demands in logistics service supply chain. *Production Planning & Control*, *26*(3), 178–202. doi:10.1080/09537287.2013.879747

Luppold, W., & Bumgardner, M. S. (2015). Examination of worldwide hardwood lumber production, trade, and apparent consumption: 1995-2013. *Wood and Fiber Science: Journal of the Society of Wood Science and Technology*, *47*, 283–294.

Nicholls, D., & Bumgardner, M. (2018). Challenges and opportunities for North American hardwood manufacturers to adopt customization strategies in an era of increased competition. *Forests*, *9*(4), 186. doi:10.3390/f9040186

Ressel, J. (2002). Hochwertiges Brettschichtholz aus Buche [High-quality glued laminated beech wood] *Vol. 107*. Holz- Zentralblatt (pp. 1269). DRW-Verlag.

Saghiri, S. (2011). A structural approach to assessing postponement strategies. Construct development and validation. *International Journal of Production Research*, *49*(21), 6427–6450. doi:10.1080/00207543.2010.531774

Servare Junior, M. W. J., Cardoso, P. A., Cruz, M. D. A., & Paiva, M. H. M. (2018). Mathematical model for supply chain design with time postponement. *TRANSPORTES*, *26*(4), 1–15. doi:10.14295/transportes.v26i4.1324

Torno, S., Knorz, M., & van de Kuilen, J.-W. (2013). Supply of beech lamellas for the production of glued laminated timber. *ISCHP 2013: International Scientific Conference on Hardwood Processing* (pp. 210–217), Florence (Italy).

Trentin, A., Salvador, F., Forza, C., & Rungtusanatham, M. J. (2011). Operationalising form postponement from a decision-making perspective. *International Journal of Production Research*, *49*(7), 1977–1999. doi:10.1080/00207541003657388

Van Kampen, T., & Van Donk, D. P. (2014). Coping with product variety in the food processing industry: The effect of form postponement. *International Journal of Production Research*, *52*(2), 353–367. doi:10.1080/00207543.2013.825741

Waller, M., Dabholkar, P. A., & Gentry, J. J. (2000). Postponement, product customization, and market-oriented supply chain management. *Journal of Business Logistics*, *21*, 133–159.

Wilson, S. (2018). Mix flexibility optimisation in hybrid make-to-stock/make-to-order environments in process industries. *Cogent Engineering*, *5*, 1. doi:10.1080/23311916.2018.1501866