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

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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

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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.

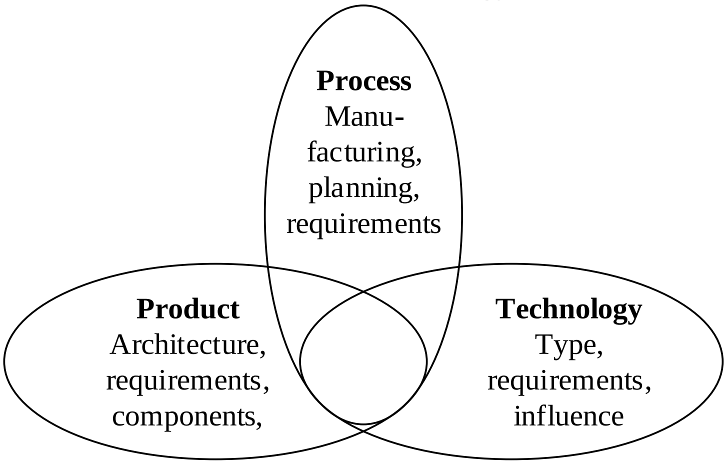


Fig. 1. The interlinked parameter product, process and technology are represented with further included aspects. The intersections show the links between two or all three aspects.

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).

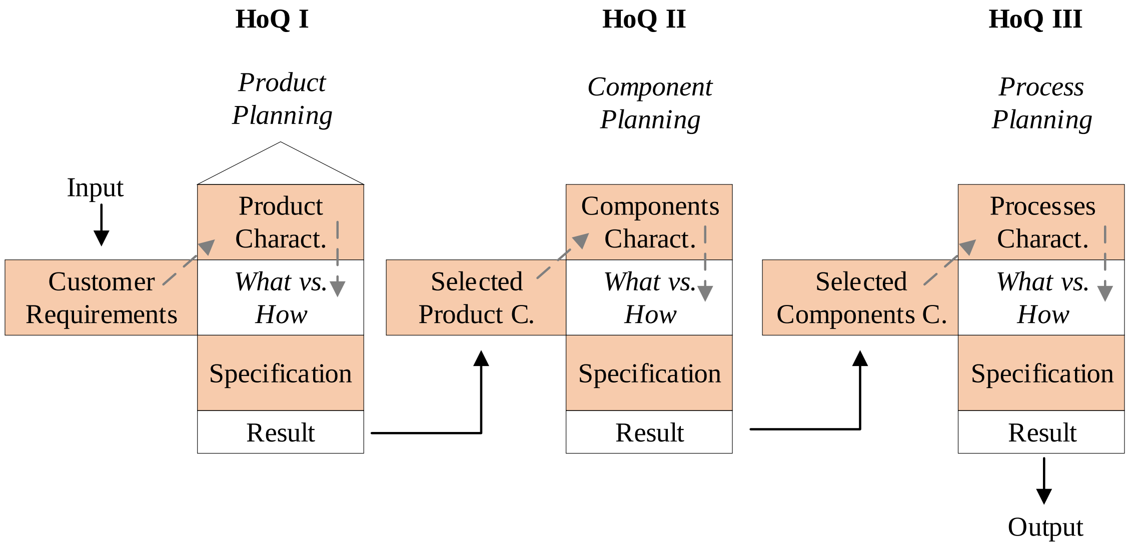


Fig. 2. The three House of Qualities are combined to the multi-step approach. The pre-defined requirements of the HoQ I are the initialization to develop the first HoQ. With the HoQ I relationship matrix, the user determined the influence of product quality characteristics on the pre-defined requirements. 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).

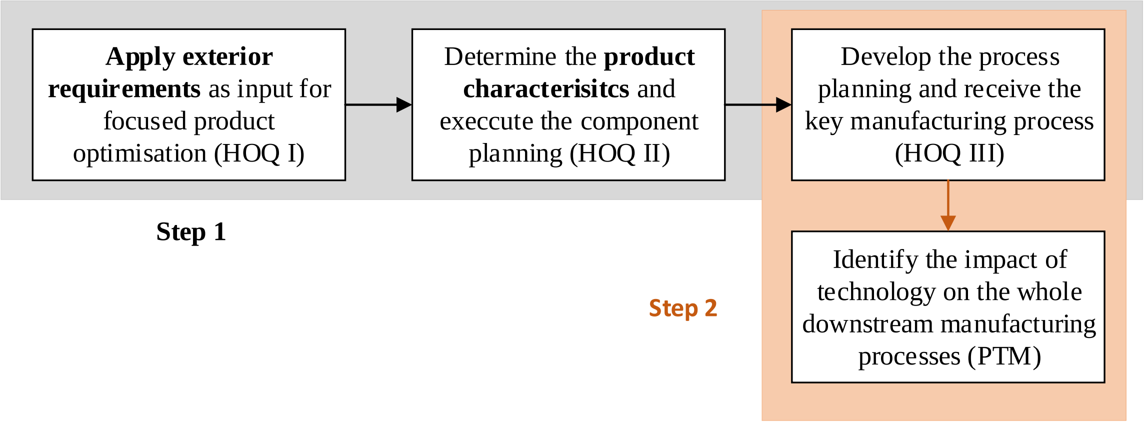


Fig. 3. An overview of the entire methodological process. Step one consists of the execution of the three HoQ. Step two comprises the transition from HoQ III to the PTM and the execution of it.

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.

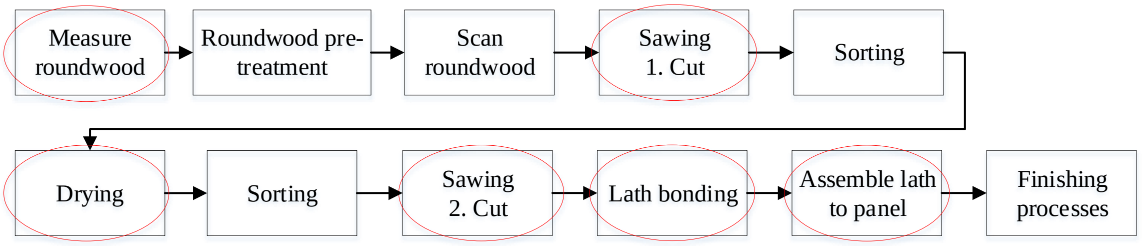
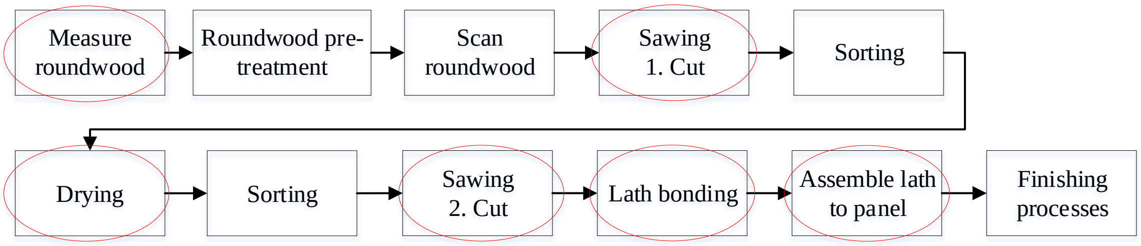


Fig. 4. The process chain for the SH panel is represented. The red cycles are the most important processes if the component requirements from HoQ II are taken into account.

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.



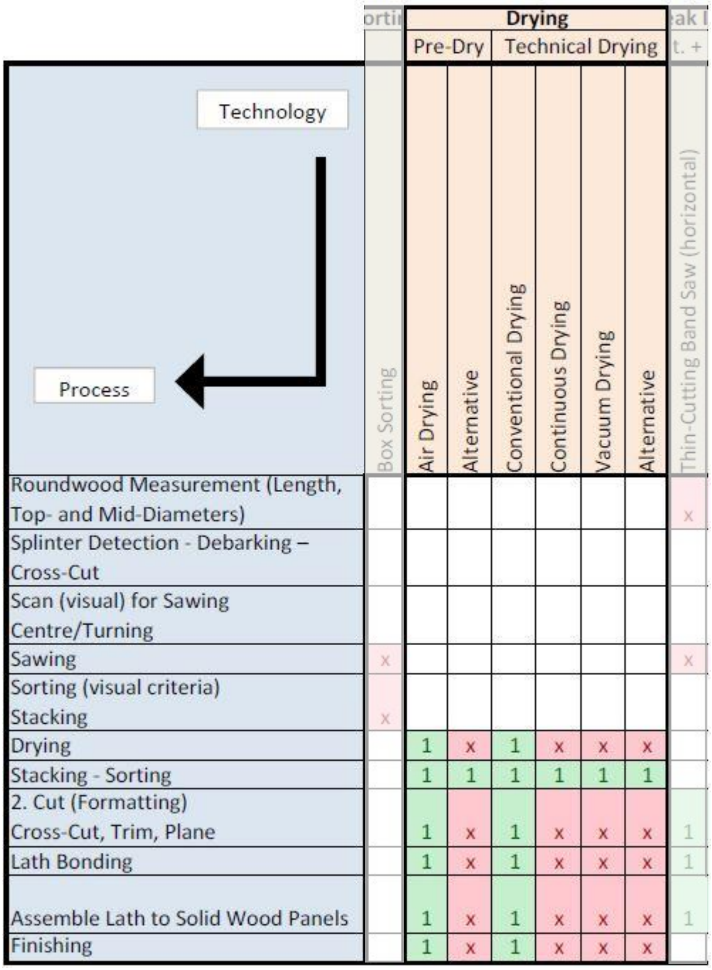
Process-technology matrix

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.



	ortin	Drying						ak l
		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).

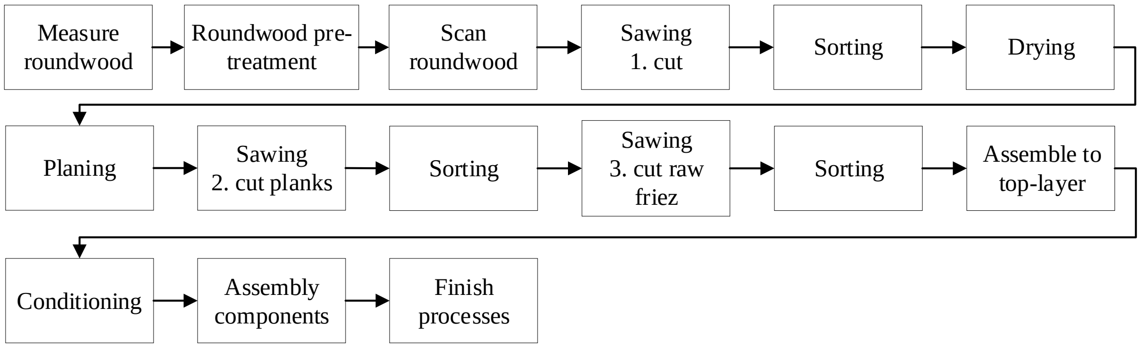


Fig. 6. The general process chain is represented for the solid parquet production.

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).

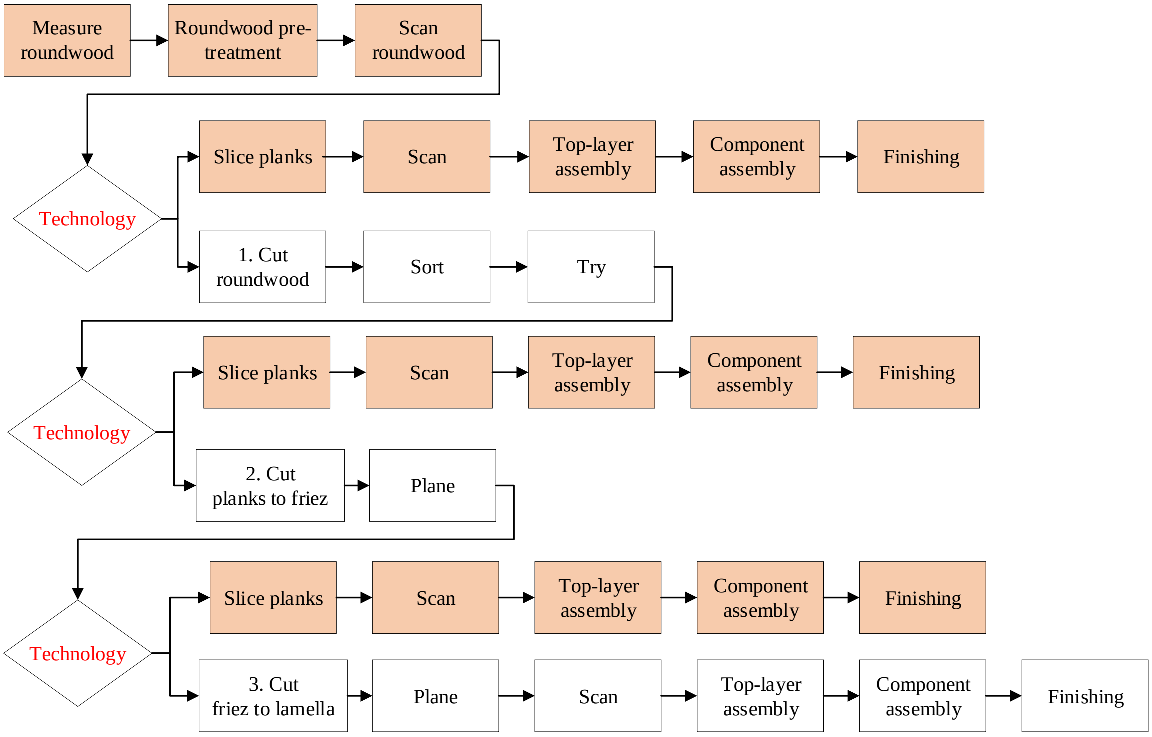


Fig. 7. The divergent process chain is represented for the solid parquet production. It is a result of the general process chain development by QFD in combination with the Process-Technology Matrix. The branching happened at the technology selection. Here, every technology branch represents either a 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).

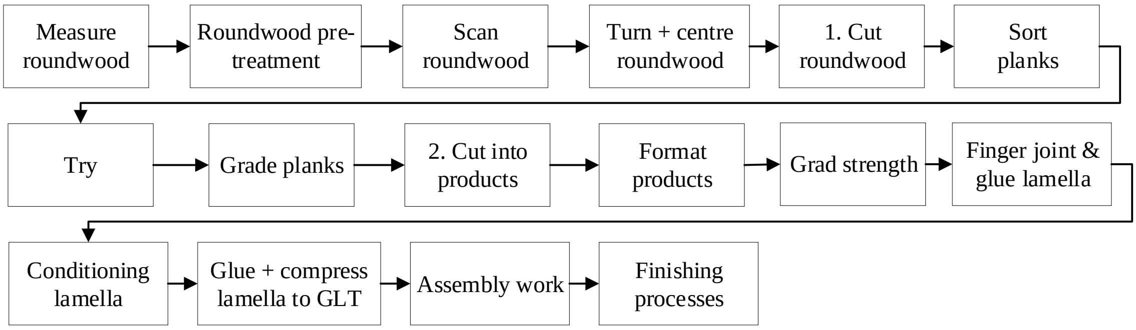


Fig. 8. The general process chain is represented for the hardwood GLT

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

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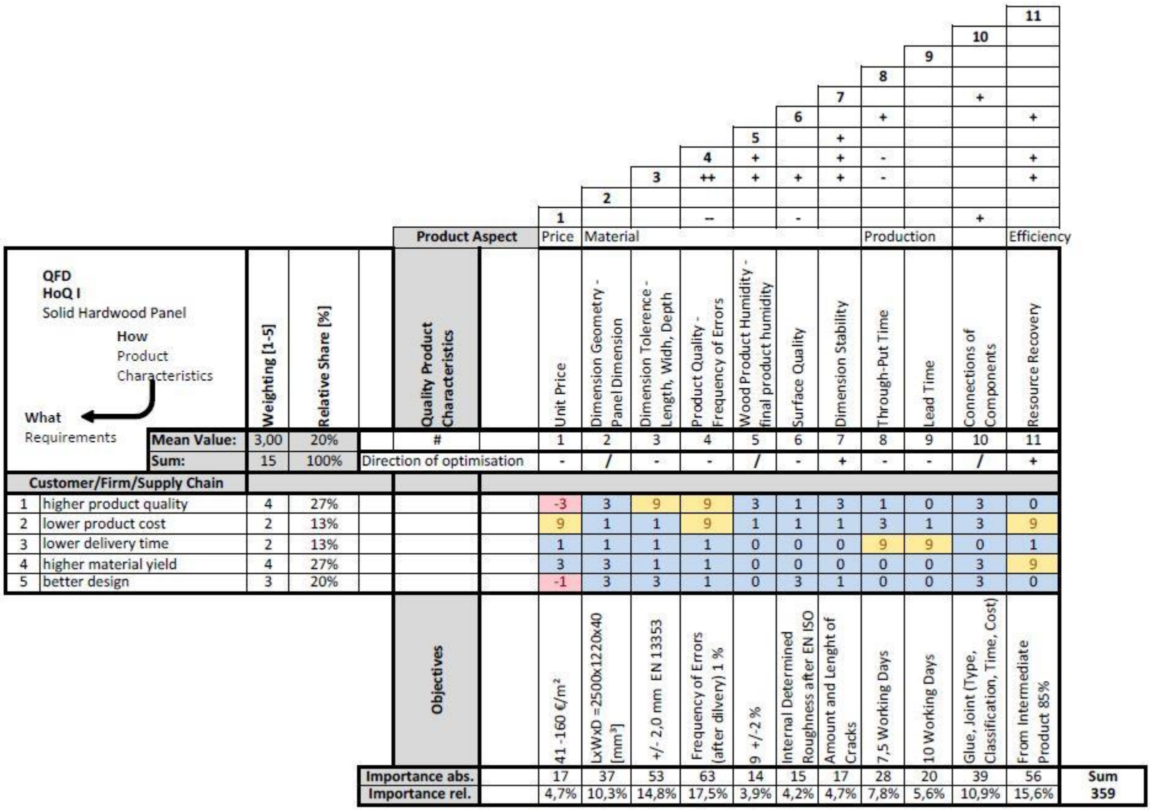
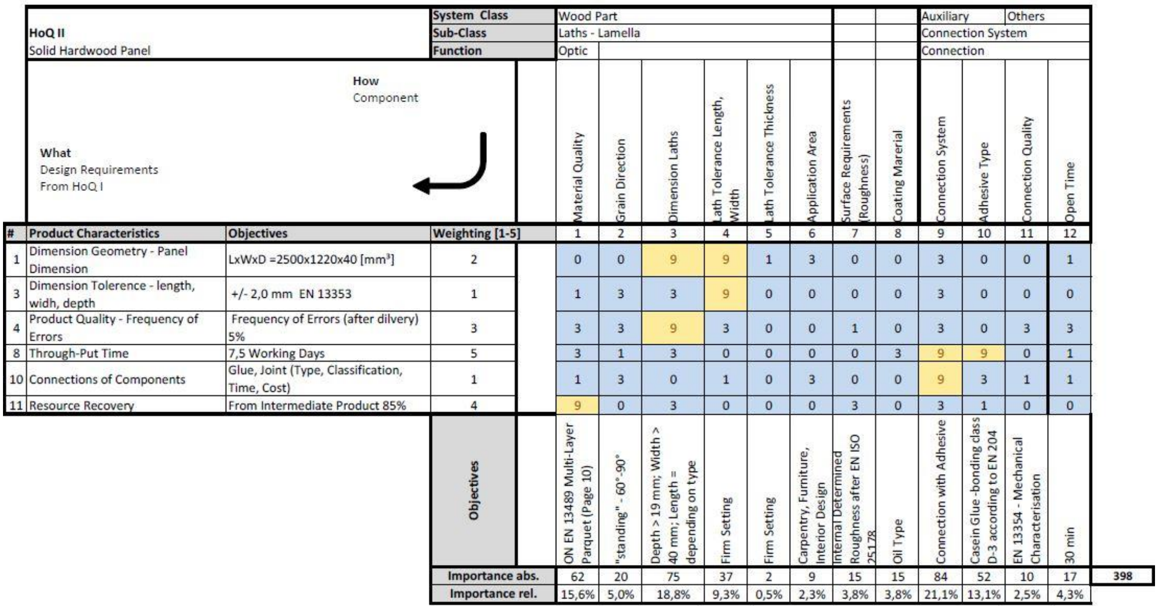
DOI: 10.15376/biores.14.1.2229-2255

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



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

	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	
				Product Aspect	Price	Material						Production			Efficiency	
	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	Sum
				Importance rel.	4,7%	10,3%	14,8%	17,5%	3,9%	4,2%	4,7%	7,8%	5,6%	10,9%	15,6%	359



	HoQ II Solid Hardwood Panel			System Class	Wood Part								Auxiliary		Others	
				Sub-Class	Laths - Lamella								Connection System			
				Function	Optic								Connection			
	What Design Requirements From HoQ I	How Component			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
#	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%

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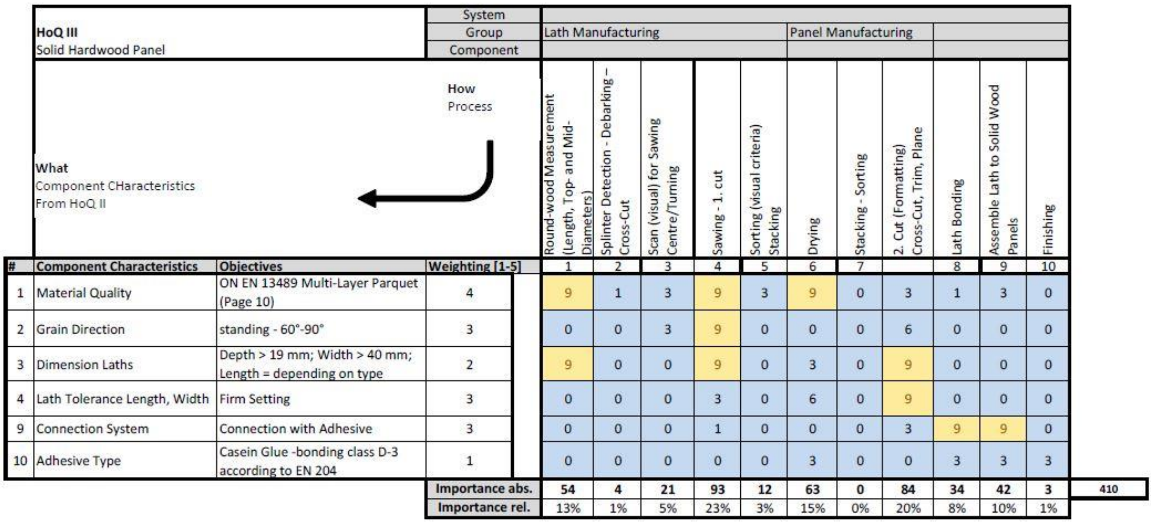
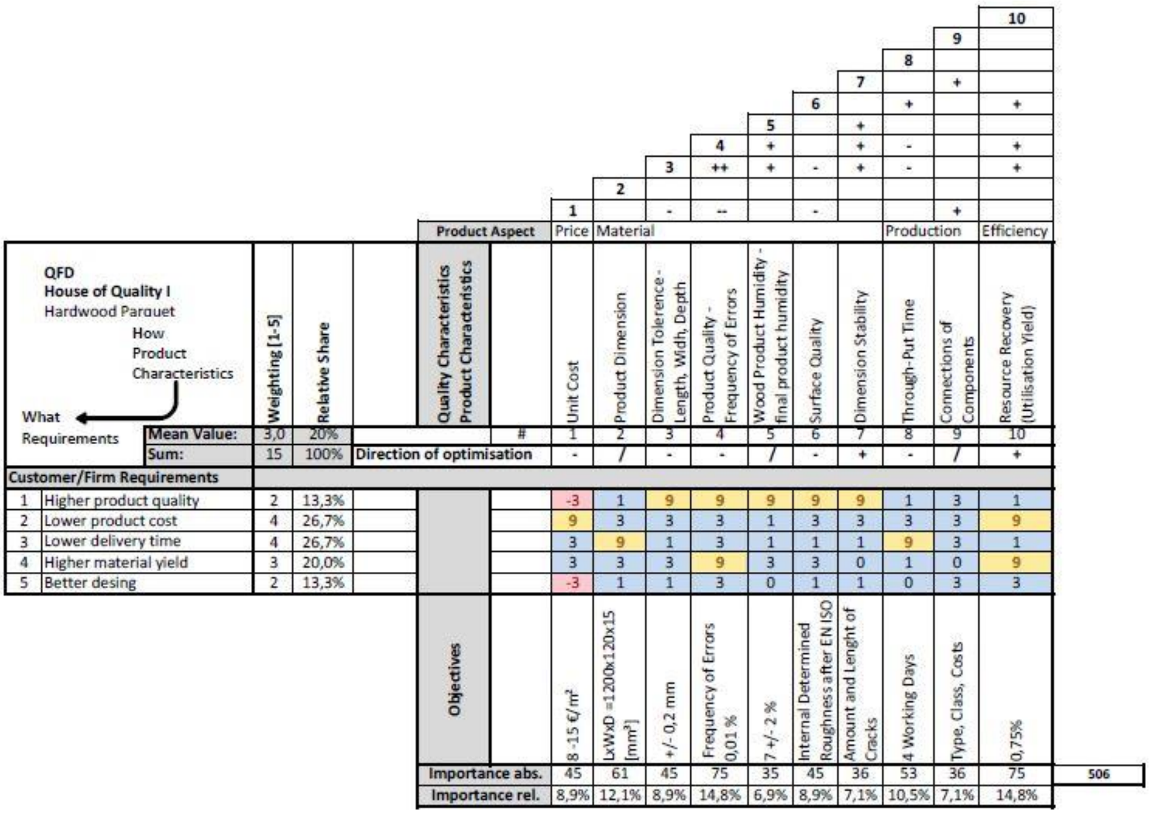


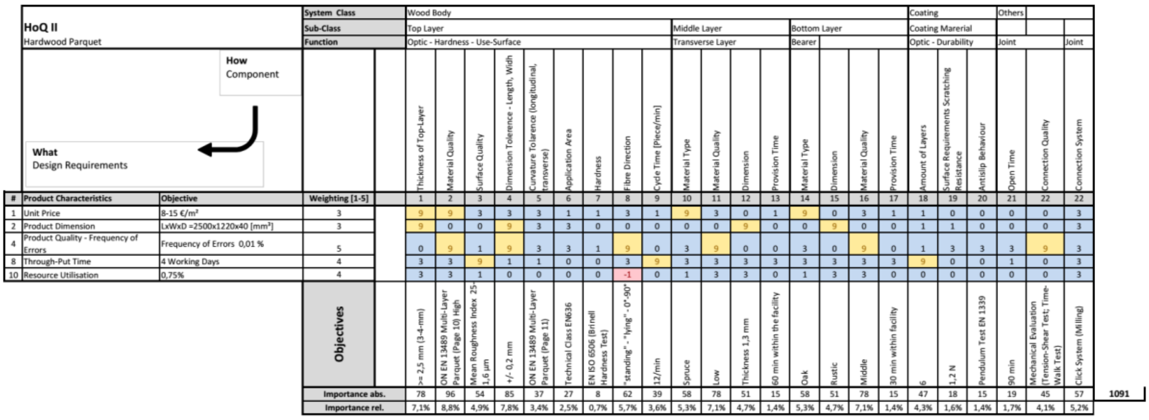
HoQ III Solid Hardwood Panel			System Group Component	Lath Manufacturing					Panel Manufacturing						
What Component CHaracteristics From HoQ II			How Process	Round-wood Measurement (Length, Top- and Mid-Diameters)	Splinter Detection - Debarking – Cross-Cut	Scan (visual) for Sawing Centre/Turning	Sawing - 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	
#	Component Characteristics	Objectives	Weighting [1-5]	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

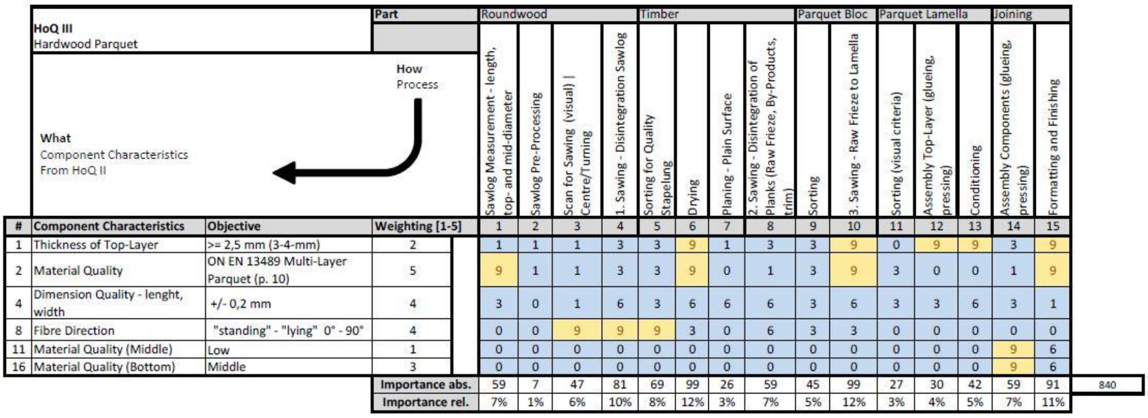


									10
								9	
							8		
						7		+	
					6		+		+
				5		+			
			4	+		+	-		+
		3	++	+	-	+	-		+
	2								
1		-	--		-			+	

QFD House of Quality I Hardwood Parquet How Product Characteristics What Requirements		Weighting [1-5]	Relative Share		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)	
					Product Aspect		Price	Material						Production		Efficiency	
	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	506
					Importance rel.		8,9%	12,1%	8,9%	14,8%	6,9%	8,9%	7,1%	10,5%	7,1%	14,8%	

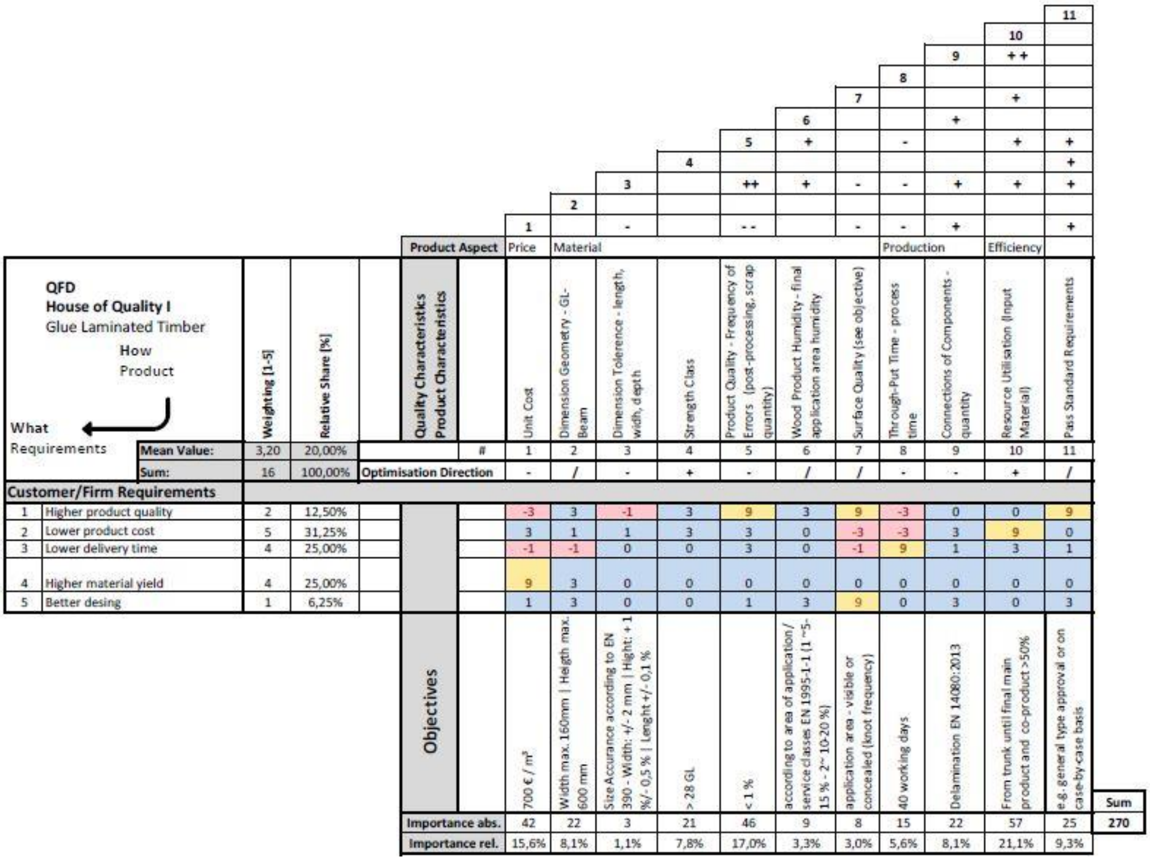


HoQ II Hardwood Parquet How Component What Design Requirements					Thickness of Top-Layer	Material Quality	Surface Quality	Dimension Tolerence - Length, Widh	Curvature Tolarence (longitudinal, transverse)	Application Area	Hardness	Fibre Direction	Cycle Time [Piece/min]	Material Type	Material Quality	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	
			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	
#	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	1091
			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%	



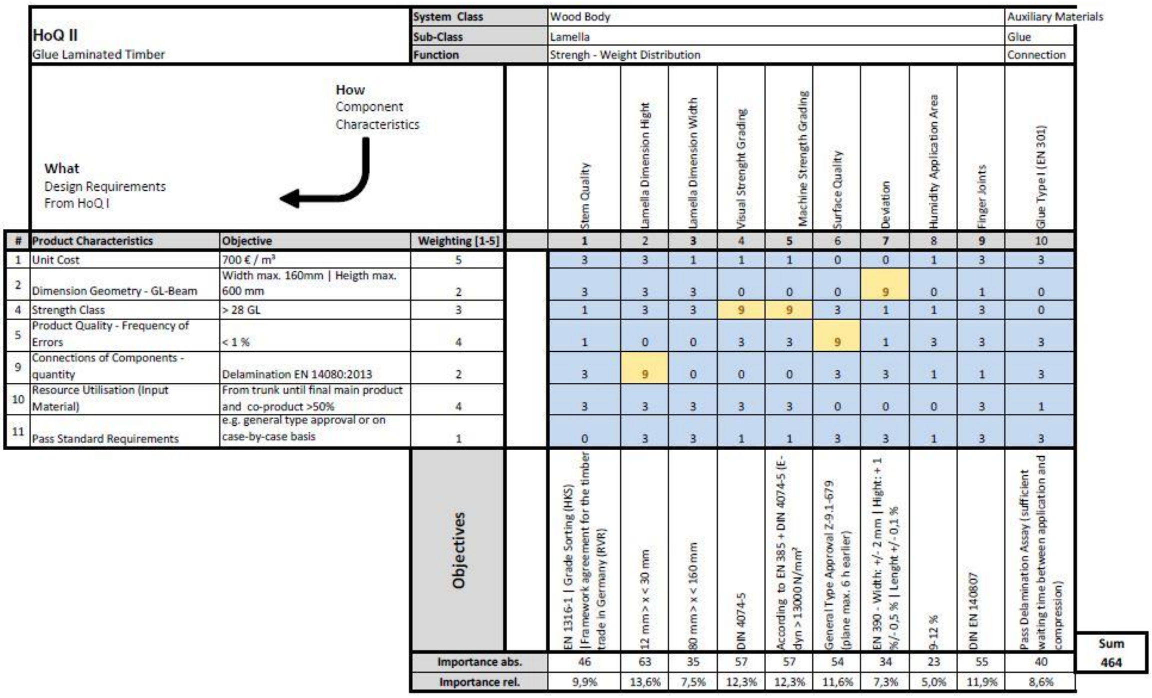
HoQ III Hardwood Parquet How Process What Component Characteristics From HoQ II			Part	Sawlog Measurement - length, top- and mid-diameter	Sawlog Pre-Processing	Scan for Sawing (visual) | Centre/Turning	1. Sawing - Disintegration Sawlog	Sorting for Quality Stapelung	Drying	Planing - Plain Surface	2. Sawing - 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	
				Roundwood				Timber				Parquet Bloc		Parquet Lamella			Joining		
#	Component Characteristics	Objective	Weighting [1-5]	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	840
			Importance rel.	7%	1%	6%	10%	8%	12%	3%	7%	5%	12%	3%	4%	5%	7%	11%	

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

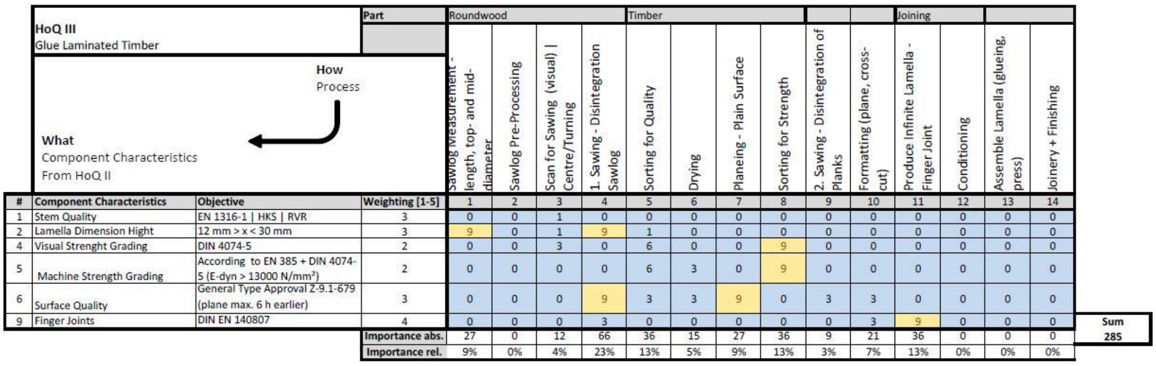


	1	2	3	4	5	6	7	8	9	10	11
1			-		- -		-	-	+		+
2											
3					++	+	-	-	+	+	+
4											+
5						+		-		+	+
6									+		
7										+	
8											
9										++	
10											
11											

QFD House of Quality I Glue Laminated Timber How Product What Requirements		Weighting [1-5]	Relative Share [%]	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	
				Product Aspect	Price	Material						Production		Efficiency		
	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	Sum
				Importance abs.	42	22	3	21	46	9	8	15	22	57	25	270
				Importance rel.	15,6%	8,1%	1,1%	7,8%	17,0%	3,3%	3,0%	5,6%	8,1%	21,1%	9,3%	



HoQ II Glue Laminated Timber			System Class	Wood Body									Auxiliary Materials	
			Sub-Class	Lamella									Glue	
			Function	Strengh - Weight Distribution									Connection	
What Design Requirements From HoQ I		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 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)	Sum
			Importance abs.	46	63	35	57	57	54	34	23	55	40	464
			Importance rel.	9,9%	13,6%	7,5%	12,3%	12,3%	11,6%	7,3%	5,0%	11,9%	8,6%	



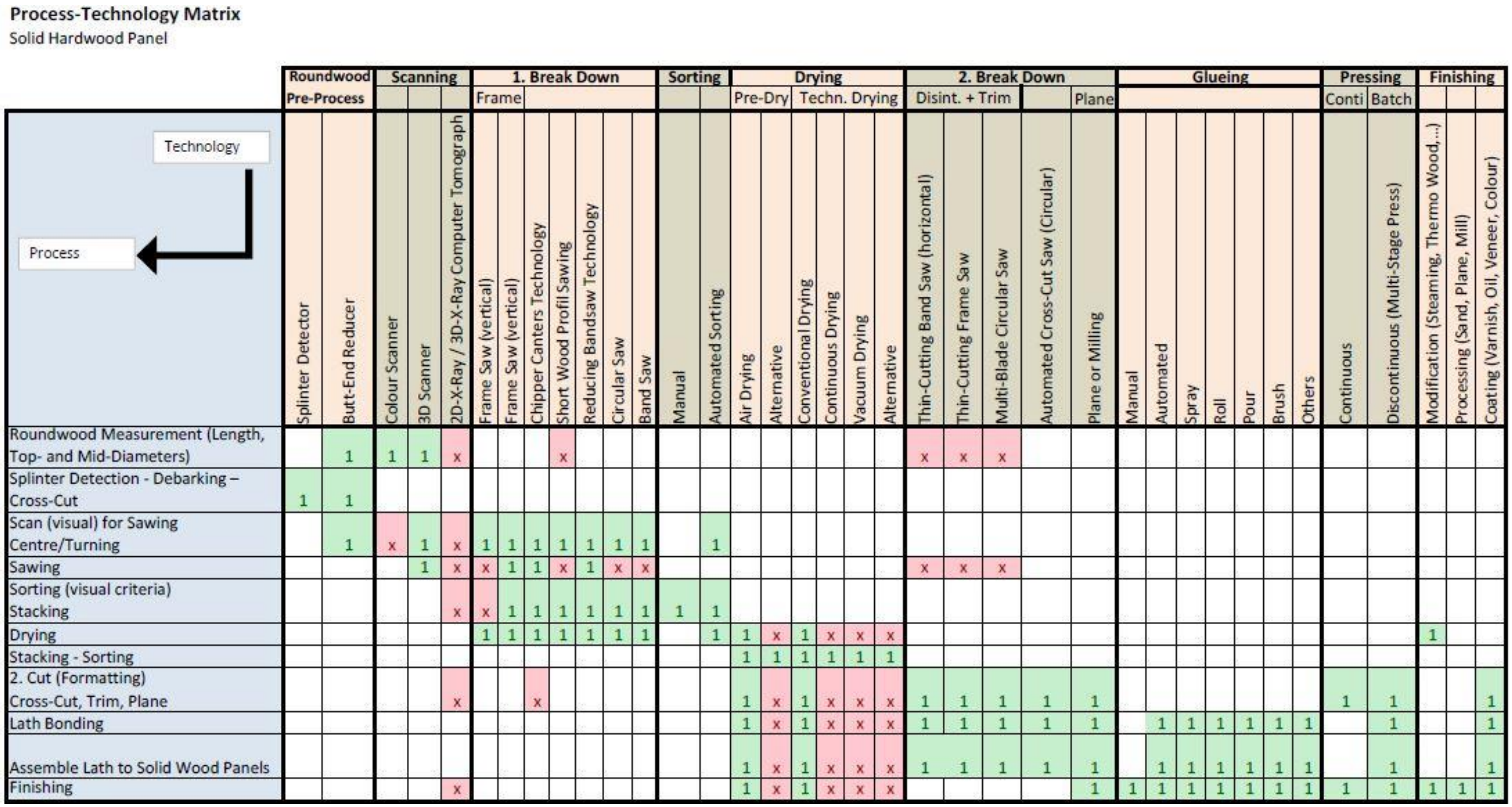
HoQ III
Glue Laminated Timber

How
Process

What
Component Characteristics
From HoQ II

			Part	Roundwood				Timber						Joining				
				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

	Roundwood		Scanning			1. Break Down							Sorting		Drying						2. Break Down					Glueing							Pressing		Finishing		
	Pre-Process					Frame									Pre-Dry		Techn. Drying				Disint. + Trim				Plane								Conti	Batch			
Technology Process	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

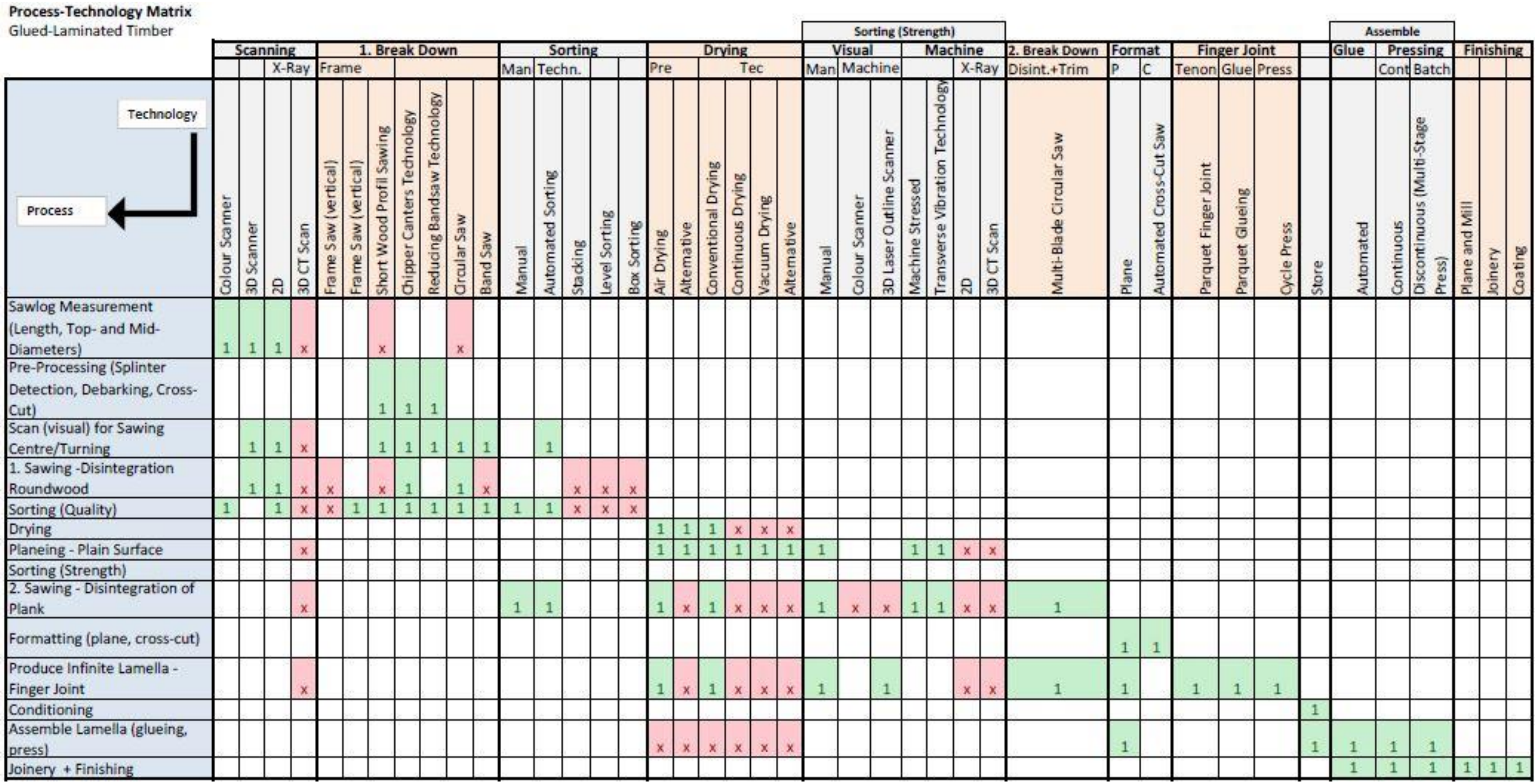
Process-Technology Matrix
Hardwood Parquet

Technology Process	Scan			1. Break Down								Sorting			
	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
Roundwood Measurement (Length, Top- and Mid-Diameters)	1	1	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
Sorting (visual criteria) Stacking	1		x	x	1	1	1	1	1	1	1	1	1	x	x
Drying											1		1		
Planeing - Plain Surface											1				
2. Sawing - Disintegration of plank (Raw Frieze + By-Products; trim)	1		x	1							1				
Sorting											1				
3. Sawing - Raw Frieze to Lamella			x								1				
Sorting (visual criteria)											1				
Assembly Top-Layer (glueing, pressing)											1				
Conditioning											1				
Assembly Components (glueing, pressing)											1				
Formatting and Finishing											1				

Technology Process	Drying						P	C	2. Break Down				Sort	
	Pre-Dry		Techn.						Disint.+Trim			Alter.	Tec	
	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
Roundwood Measurement (Length, Top- and Mid-Diameters)									x	x	x			
Pre-Processing (Debarking, Cross-Cut,ect)														
Scan (visual) for Sawing Centre/Turning														
1. Sawing -Disintegration Roundwood									x	x	x			
Sorting (visual criteria) Stacking														
Drying	1	x	1	x	x	x								
Planeing - Plain Surface							1	1						
2. Sawing - Disintegration of plank (Raw Frieze + By-Products; trim)		x	1	x	x	x	1		1	1	1	1		
Sorting	1	1	1	1	1	1			1	1	1	1	1	1
3. Sawing - Raw Frieze to Lamella	1	x	1	x	x	x	1		1	x	1	1		1
Sorting (visual criteria)	1	1	1	1	1	1						1		1
Assembly Top-Layer (glueing, pressing)	1	x	1	x	x	x						1	1	1
Conditioning	x	x	x	x	x	x						1		
Assembly Components (glueing, pressing)	x	x	x	x	x	x						1		
Formatting and Finishing												1		

Technology Process	3. Break Down				Sort	Top-Layer			Condition		Assemble			Finishing		
						Glue	Pressing				Glue	Pressing				
	Standard			Alter.	Tec		Conti	Batch				Conti	Batch			
	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)																
Pre-Processing (Debarking, Cross-Cut,ect)																
Scan (visual) for Sawing Centre/Turning																
1. Sawing -Disintegration Roundwood																
Sorting (visual criteria) Stacking																
Drying																
Planeing - Plain Surface																
2. Sawing - Disintegration of plank (Raw Frieze + By-Products; trim)																
Sorting																
3. Sawing - Raw Frieze to Lamella	1	1	1	1												
Sorting (visual criteria)	1	1	1	1	1											
Assembly Top-Layer (glueing, pressing)	1	1	1	1	1	1	1	1								
Conditioning				1		1	1	1	1	1						
Assembly Components (glueing, pressing)				1		1	1	1	1	1	1	1	1			
Formatting and Finishing				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

																						Sorting (Strength)														Assemble					
	Scanning				1. Break Down							Sorting					Drying						Visual			Machine				2. Break Down	Format		Finger Joint				Glue	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