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ScienceDirect

Procedia CIRP 136 (2025) 123–128

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Development of a Requirement-Oriented Design Approach for Integrating Wood into Vehicle Components

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Abstract

The resource wood has been optimized by nature for millions of years, leading to its exceptional lightweight potential for numerous applications. This study examines the potential of wood as a lightweight material in the automotive sector, considering its multitudinous advantageous properties. Given the stringent requirements of the industry, uncertainty exists regarding wood integration methods and forms. Therefore, requirements were identified, analyzed and used to derive requirement-oriented design approaches. Thus, this research study explores an innovative technology for embedding wood into vehicle body components, incorporating ecofriendly design principles. Preliminary simulation results reveal significant weight reduction potentials.

Keywords: Design for Sustainability; Ecofriendly Design; Natural Lightweight Materials; Requirement-oriented Design; Innovative Lightweight Solutions

1. Introduction

Wood has been optimized by nature over hundreds of millions of years. Its potential for lightweight design in the automotive sector is promising [1] and warrants a thorough investigation into its specific benefits. However, the stringent requirements for automotive components create uncertainties regarding suitable integration methods and forms, necessitating the development of technologies that meet these exacting demands. Therefore, an integrative methodological approach is proposed, starting with the identification and comprehensive analysis of requirements and followed by the derivation of design concepts tailored to meet these requirements. The study culminates in a case study focused on the new and innovative wood-plastic-hybrid technology. Using reference components, this study assesses the specific lightweight potential of incorporating wood into vehicle body components while adhering to environmentally sustainable design principles.

2. State of the art

During the development of new or the redesign of existing vehicle components it is crucial to identify their requirements in the early phase of the product development process [2, 3]. For this purpose, established methodological approaches are presented. Next, a systematic material analysis of wood is conducted, highlighting its potential as a lightweight material. Thereafter, the presentation of hybrid components and their manufacturing processes is followed by a section on the modeling and simulation of veneer-based composites.

2.1. Requirements management during the early phase

During the early phase of product development, the influence on the product design is high, though data availability is very limited. Thus, it is an important phase of the

10.1016/j.procir.2025.08.023

development process, albeit one that is fraught with uncertainties. [4–6] To address this challenge, extensive knowledge of the requirements placed on the product to be developed is a key aspect of this phase. Various methodological approaches exist for identifying requirements, which can be interconnected and combined [7, 8]. The V-Model, as exemplified in VDI 2221, provides an overview of handling requirements. It divides them into multiple system levels and can aid in the concretization of overarching requirements. [9, 10] The reference system analysis helps identifying requirements by analyzing already validated systems [11, 12]. *Ehrlenspiel* introduces several methods as an approach for requirements identification as well as categorization [2]. The ISO 25010 standard categorizes requirements into functional and non-functional, with the latter further subdivided into quality and constraints [13].

2.2. Wood as a lightweight material in the automotive context

The identification of requirements can be followed by a systematic material selection [3]. Based on a defined bending load case and an optimization objective, a mass requirement index can be derived, from which a guideline is established. The identification of suitable lightweight materials is conducted by parallel translation of the guideline into the top-left corner of the material diagram shown in figure 1, which is equivalent to the minimization of the derived mass index.

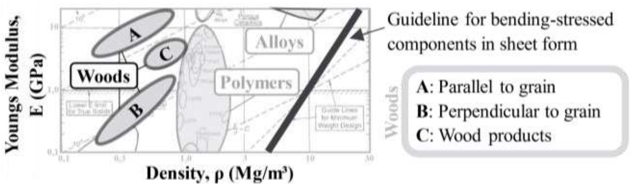

Fig. 1. Systematic material selection for planar bending-stressed components and wood as a lightweight material [3].

In the case of a bending plate, wood emerges as one of the best possible lightweight materials.

2.3. Hybrid components and their manufacturing process

The high-volume plywood production process combines a steaming of the tree trunks with a non-cutting rotary peeling to efficiently produce continuous veneers and minimize waste during the production process. The veneers are portioned, sorted, coated with adhesive and layered. Subsequently, the layered veneers are pressed under the influence of pressure and temperature. During this step, integrated forming can occur. The final product is a wood composite. [14, 15]

Multi-material design can be divided into composites and combined materials, which can be combined through a bonding zone. Hybrid product design is a part of combined materials, where a macroscopically inhomogeneous hybrid material is created [16]. When components are joined in a one-step process, where the hybrid composite is created through a primary forming or reshaping process, the resulting component is referred to as an intrinsic hybrid. For example, metal sheets with holes can be placed into an injection molding machine, causing the injection molding material to penetrate the holes, thus achieving intrinsic bonding and the hybrid structure. Compared to traditional joining methods, such as riveting or bolting, this component integration can lead to a lightweight-optimized component and reduce manufacturing effort. [17] This mechanism is based on a form fitting. For instance, if force transmission is realized through form elements, it is referred to as a form fit. A force fit occurs when frictional forces are generated through clamping, counteracting the displacement forces to be transmitted. [18]

2.4. Modeling and simulation of veneer-based composites

Wood materials used as veneer laminates exhibit complex behavior. Specifically, the individual veneer layers, their orientation, and the bonding within them lead to varying global behavior of the wood material depending on the chosen overall composite structure. As an anisotropic material, wood can be represented using an orthotropic material model. When multiple layers of veneer are stacked, various modelling and simulation approaches exist for investigating these veneer-based composite structures. One possibility is to use computed tomography scans to precisely identify the material properties of both the veneer layers and the composite, including adhesive distribution and penetration. This method enables the analysis of defects and their propagation through simulations. [19] Additionally, it can be assumed that minor material deviations may be compensated within the overall composite structure [20]. Furthermore, examining the manufacturing process and its effect on the overall composite structure allows for the comprehensive study of its properties [21]. The dynamic behavior and failure mechanisms under crash scenarios can also be investigated [22].

3. Research needs and research objectives

As shown in the previous section, several approaches for requirements identification are available. Theoretically derived lightweight potentials in accordance with the systematic material selection are expected by using wood but have not been utilized in mass produced vehicle components so far. The objective is to utilize these potentials and to investigate whether and how these lightweight potentials can be maintained in practice for complex vehicle components. This study therefore aims to answer the following research questions.

- How can wood, considering the high diversity and complexity of requirements for vehicle components, be used for semi-structural vehicle parts?
- Can the expected lightweight potentials be realized in vehicle components while simultaneously addressing the high component requirements in the automotive context?

To answer these questions, it is necessary to explore the structural use of wood in the automotive context, particularly in relation to the stringent requirements placed on the components. For this purpose, a new technology must be realized, which addresses specific requirements and enables the integration of wood into vehicle components through the synthesis of requirement-driven partial solutions. Therefore, the new wood-plastic-hybrid technology was developed, which embodies requirement-oriented design solutions. Subsequently, this technology was investigated through simulations regarding its lightweight potential. The overarching investigative approach of this study was ultimately applied in a case study, in which three different components of the Porsche Taycan (Type J1) were analyzed.

4. The new wood-plastic-hybrid technology

The wood-plastic-hybrid technology is an innovative approach for integrating wood into vehicle components. It includes a topology-optimization based targeted alignment of veneers building a composite, which constitutes the foundation of the technology. Whilst pressing the veneers, geometrical forming processes and coating steps can occur. Finally, the composite is included within an injection molding process.

During the design stage of the technology components, the wood structure reflects the main load-bearing structure, while the plastic ensures the freedom of form of the components. Two-dimensional deformations can be represented by the wood composite, whereas a three-dimensional geometry can almost exclusively be represented by the plastic structure. By coupling surfaces, the proportion of wood composite can be increased. This material synthesis enables the design of complex geometries. Furthermore, the proportions of wood and plastic in the overall component can be varied. For example, a maximization of the wood material proportion can be ensured by designing all surfaces in wood-composite structures. However, this increases the wood material forming process effort, as a multi-side press and a multi-step forming process are required. Reducing the process complexity in a different design approach, the forming process is facilitated by two efficiently formable L-profiles, which, however, increases the proportion of plastic. To illustrate this, figure 2 shows these two contrasting design approaches shown on the Frunk of the Porsche Taycan (Type J1).

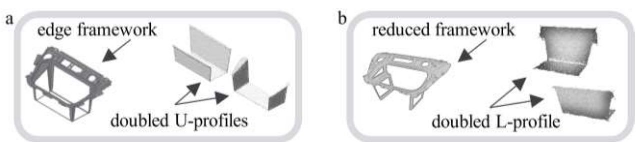

Fig. 2. (a) maximized wood approach; (b) simplified process approach.

Before the injection molding process, the wood composite must be adjusted to a target moisture level, as wood, being a hygroscopic material, absorbs moisture that can affect the injection molding process. The specific target moisture level of the wood material depends on both the component design and the injection molding parameters and must be adjusted individually for each design. Through the injection molding process, several fitting mechanisms occur. Microscopic form fits can be achieved via natural and optionally technically added surface structuring of the wood surface. Furthermore, the depiction of the form-fit intrinsic bonding within the transition zone between the wood material and the plastic clamp structure highlights two advantages: First, the form fit within the bonding zone is enhanced by combining microscopic with macroscopic form fits through the intrinsic bonding. Second, targeted counteraction is provided against the delamination of the bracket structure due to shrinkage after the injection molding process. This helps prevent high scrap rates and later failure patterns in overall components concerning moisture intrusion into the wood material. Furthermore, the shrinkage can lead to additional force fitting as a supplement to the form fit. These fitting mechanisms are illustrated in figure 3.

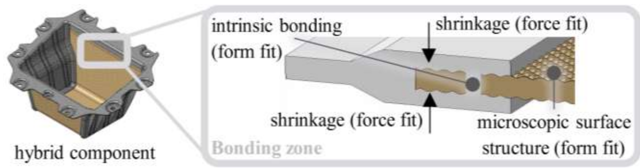

Fig. 3. Hybridization, bonding zone clamp and fitting processes [23].

The wood composite profiles exhibit tolerance variations. Global tolerances are compensated by pressing forces of the injection molding machine. Thickness variations are managed by pressure profiles located at the back of the clamp structures, locally increasing pressure forces and thus preventing bypasses of the pressing-surfaces of the molding machine.

5. Requirement-oriented technology design concepts

To apply the new wood-plastic-hybrid technology for vehicle components, it is necessary to investigate the component requirements in the first place [2, 3]. Based on these findings, requirement-oriented technological design solutions will be developed. These solutions will be consolidated into an overall component, thereby enabling the realization of wood-plastic-hybrid components.

5.1. Integrative approach for the requirement identification

An integrative methodological approach was employed to identify the requirements. By combining the following requirement identification methodologies, the risk of missing technology- and component-relevant requirements that could impact the technology design is significantly reduced. During the *reference system analysis (RSA)*, existing requirements pertaining to reference systems are identified. For vehicle components, the focus is set on reference objects, their specific configuration and especially on previous product generations. The *geometric component analysis (GCA)* includes the derivation of requirements from the geometry, additionally providing a preliminary assessment of technology suitability based on the predicted lightweight potential. Whilst the *analysis of sketches and requirement lists (ASR)* an expansion of requirements and detailing of existing technology requirements can be achieved. *Expert interviews (EI)* enable the use of undocumented experiential knowledge. Therefore, an augmentation of the requirement spectrum can be realized. The *requirement categorization (RC)* establishes a foundation for the further expansion of requirements, whereas the *process analyses of technology manufacturing (PA)* enables a process-oriented technology analysis for requirement specification as well as requirement enhancement. Requirements, along with their specific characteristics and the knowledge of potential influencing factors, are dispersed across various sources. By merging data-analyzing methodologies (*RSA, GCA, ASR*) with investigative and expansive approaches (*EI*, *RC*), supplemented by a process-centric influence analysis (*PA*), a comprehensive spectrum of potential requirement sources is scrutinized. Given the significant impact of decisions made in the early development phase, this methodology helps reduce the risk of errors in the later product development phases.

5.2. Requirement-oriented partial technology design concepts

Since being highly dependent on environmental influences, the new wood-plastic-hybrid technology necessitates the requirement-oriented specification of technology-specific features. The technology-oriented requirements are identified through the previously introduced integrative approach, leading to over 30 individual requirements. In figure 4, an excerpt of the requirement list is shown.

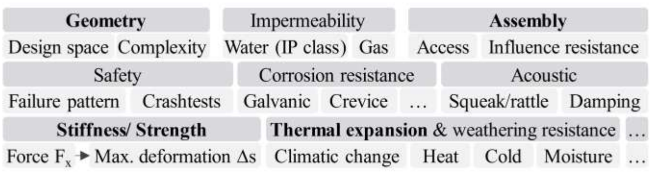

Fig. 4. Excerpt from the list of requirements generated by the approach.

Each of the aforementioned requirements is subsequently elaborated upon, accompanied by a detailed illustration of the concrete manifestation. The requirement-driven implementation of design solutions is illustrated using four exemplary requirements, which are printed in bold in figure 4.

Stiffness and strength. The favorable mechanical wood-properties preferably result in significant lightweight potential if its fibers are retained within the component. Consequently, veneer layers of variable thickness are employed in the technological implementation. **Thermal expansion**. Vehicle components are subjected to wide temperature ranges. The combination of individual wood veneers in the form of cross-laminated layers counters significant anisotropic thermal expansion. **Representation of geometric complexity**. Veneer laminates made from wood exhibit two-dimensional formability but are challenging to deform in three-dimensional geometries. Through the synergy between the wood material as veneer laminates and a largely form-free plastic structure, complex geometrical shapes can be efficiently depicted, which are necessary to implement the technology into complex vehicle component designs. **Assembly capability**. Due to the cathodic dip painting process and the particularly high temperatures during drying, especially for the plastic, the technology components must be integrated during assembly.

The technology-specific features are then synthesized to create the overall hybrid component. In the realization of the clamping structure and fiber orientation it becomes evident that the fiber layers and their retained wood-fibers differ in their orientation, thereby realizing the plywood structure. The outer layers preferably exhibit a fiber orientation that runs longitudinally into the clamp structure to ensure the highest possible force transmission capability within the bonding zone. The synthesis of the respective design solution elements results in a component structure, which is detailed in figure 5.

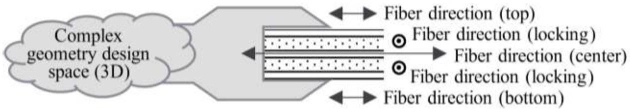

Fig. 5. Requirement-oriented clamping structure and fiber direction.

Within the clamp structure, complex geometries can be represented, helping realize complex vehicle components.

6. Technology-specific simulation approach

To ascertain the projected lightweight potential of the technology and examine various design configurations, a simulation approach combining existing approaches and applying them to the technology and its design process is employed. To validate the global composite properties used in the simulations with experimental data, the extensive experimental series from the Federation of the Finnish Forest Industry [24] was utilized. An ideal orthotropic material model was used for the simulation of the wood-veneers. The wood fiber properties perpendicular to the fiber were made analogous to the transverse properties, while differing from the longitudinal properties. The variable input parameters included the longitudinal and transverse Young's modulus and the Poisson's ratio. By this, the individual veneer layers could be characterized. Subsequently, the layers were assembled into a multi-layer-composite. The bonding within the veneer layers was assumed to be ideal, excluding delamination and separation. This approach allows for the mapping of varying veneer structures without the need to generate new real experimental results for each individual configuration.

By simulating the composite using LS Dyna (explicit, R12) as well as four load cases, the global composite properties could be determined and compared with real experimental data. Since when using plywood structures the main layer direction can be varied, it is necessary to conduct two pull tests as well as two bending tests, each including the longitudinal as well as the transverse direction, as illustrated in figure 6.

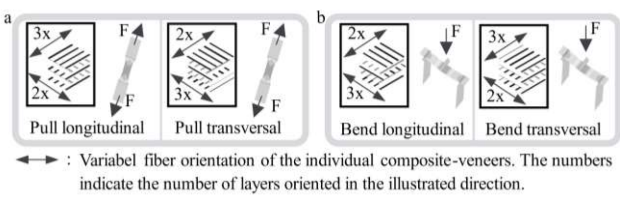

Fig. 6. (a) Pull test of the composite; (b) Bending test of the composite.

Subsequently, the input variables were varied to ensure that the global composite structure could be accurately represented by the simulation model. By repeating this procedure and identifying multiple support points, an efficient modelling of additional composite structures exceeding the experimental results was achieved. The results of this approach, in terms of material properties using a three-layered plywood structure made from birch, are illustrated in table 1.

Table 1. Accuracy of modelling three-layered birch plywood structures.

Material parameter	Simulation	Test results	Delta
E-modulus bending (longitudinal)	16471 MPa	15757 MPa	4,3 %
E-modulus bending (transverse)	1029 MPa	908 MPa	11,8 %
E-modulus pull (longitudinal)	10694 MPa	11656 MPa	-9,0 %
E-modulus pull (transverse)	6806 MPa	6013 MPa	11,7 %

Given the necessity of early-stage modelling of the new technology and the multitude of variants to be evaluated, the focus was deliberately placed on the implementation of modelling approaches that could be completed in a timely manner. These provide a sufficiently accurate modelling of the respective concepts. However, they reach their limits when it comes to accurately predicting the precise and complex behavior of the components in real component implementation scenarios. Therefore, a final design should be re-modelled with a greater focus on the adhesive penetration, its properties, and the bonding zone between wood and plastic. Nevertheless, this necessitates considerably more intricate modelling and further enquiries concerning the nascent bonding zone, which surpasses the current state of the art.

7. Integrative technology development approach

The previously presented steps were consolidated into an integrative approach for the development of wood-plastic-hybrid technology components, starting with the identification of the requirement list, which will then be transferred to the component design process. Within the design phase, each requirement is allocated to a specific design solution. By synthesizing these, the technology components are developed, which will then be analyzed regarding the fulfillment of the requirements as well as the overarching lightweight potential. This iterative process is illustrated in figure 7.

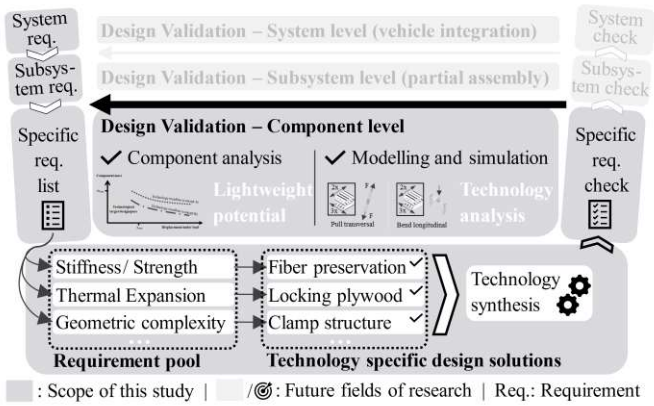

Fig. 7. Integrative approach for developing hybrid technology-components.

The requirement pool represents the individual requirements identified by the integrative approach. They are addressed with specific technology design solutions and synthesized leading to the development of components in wood-plastic-hybrid design, which are then investigated regarding their lightweight potential through the previously demonstrated modeling and simulation approach. This study thus forms the foundation for future investigations at the subsystem and system level which will then enable the integration of this new technology into vehicle components. This approach will be applied to real vehicle components in the following case study.

8. Case study: Application of the integrative approach

The integrative approach was applied on the frunk of the Porsche Taycan (Type J1) as well as its hat rack and trunk floor. These three components were chosen based on their complex requirement profile not only to evaluate the technology and the methodological approach, but also to prepare the estimation of the technology transfer potential of the new technology in other fields of application within vehicle structure.

8.1. Frunk of the Porsche Taycan (Type J1)

By applying the integrative approach, a wood-plastic-hybrid technology frunk was designed and analyzed. 127 variants were investigated and plotted in a diagram with the variant mass plotted over the displacement under load, representing the real use-case of the component in a vehicle. Each technology trendline represents a fundamental design of the component, which was further examined using sub-variants. Therefore, wood types, layer designs, fiber orientations, material thicknesses and compression levels were varied. Various types of plastics were considered, along with geometric variations such as beads and ribs in the plastic structure.

The reference component, currently produced using polypropylene with long glass fibers, is represented by the series frunk. Concept A uses a double U-profile, whereas concept B enhances the double L-profile approach by combining the overlapping bottom surfaces into a single U-profile geometry, as shown in figure 2 (a) respective (b). The study examined the displacement of the frunk's floor under the load of 1000 Newton, which is induced on the point of the surface that is most displaced under a surface load via a pressure stamp, as well as its mass. Both criteria may not surpass the values of the reference component, leading to a technological target design space, in which the target variants of the wood-plastic-hybrid technology frunk may be located at. Selected results and the trendlines are shown in figure 8.

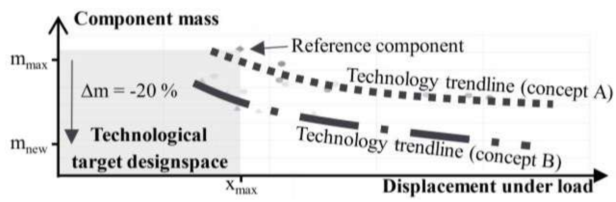

Fig. 8. Lightweight validation and technology target designspace.

By analyzing the trendlines, concept B appears to possess a higher potential for lightweight design. The target variant exhibiting a consistent displacement compared to the reference variant, achieved a lightweight design comprising 20 %.

8.2. Hat rack and trunk floor of the Porsche Taycan (Type J1)

The selection for analyzing these components in addition to the frunk allows an examination of components located within the interior, as well as in a transitional zone between the interior and exterior. This approach facilitates the exploration of further technology application fields. The trunk floor represents the ideal load case for the new technology according to Ashby's criteria. In this case, lightweight design potentials of approximately 40 % were achieved compared to the referenced steel design, while the hat rack demonstrated a lightweight design potential of approximately 30 % compared to the referenced aluminum component. All target designs exceeded the performance requirements in terms of load-specific displacement compared to their reference variants, proving the lightweight potential of the wood-plastic-hybrid technology. In future studies, it is essential to examine how additional requirements and their design solutions impact the overall lightweight potential of the specific components.

9. Discussion and further fields of research

This study and its initial simplified modeling and simulations confirmed the lightweight potential of the wood-plastic-hybrid technology. The specific design solutions demonstrated that the integrative approach for the previous requirement identification is inherently complex due to scattered information across various sources, including both documented and experiential knowledge. Expert interviews are essential to capture nuanced insights, while reference and new components provide crucial information and unforeseen aspects. As the layered structure requires specific considerations for accurate predictions, further research on real wood-plastic-hybrid components will possibly reveal new aspects, which subsequently should be integrated into the simulation approach to enhance the accuracy of the predicted lightweight potentials. While simulations are useful for conceptual comparisons, actual data is required for higher accuracy. However, any advanced simulation approaches must be evaluated for their applicability in the early phases, as overly complex modeling can hinder the essential early-stage variant comparison as shown in the introduced integrative approach.

10. Conclusion

This study introduces the new wood-plastic-hybrid technology as a solution for integrating wood as a lightweight material into vehicle structures. It fundamentally enhances our understanding of this new and innovative technology and presents requirement-specific design solutions. After combining these design solutions to a wood-plastic-hybrid component, modelling and simulation methods were used to examine the technology's lightweight potentials. The study's methodological approach was applied to three components in a case study, confirming the lightweight potentials of the wood-plastic-hybrid technology. To conclude, the subsequent research areas were identified to advance the development of the new technology. These include a detailed investigation of the hybrid bonding zone, examining the impact of varying process parameters and integrating technology components into vehicle structures, followed by a requirement-oriented technology validation on a subsystem as well as a system level.

References

[1] Kohl, D., Link, P., Böhm, S. Wood as a Technical Material for Structural Vehicle Components 40; 2016. p. 557.

[2] Ehrlenspiel, K., Meerkamm, H. Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit, 6th edn. Hanser Verlag, München, Wien; 2017.

[3] Ashby, M.F. Materials selection in mechanical design, 2nd edn. Butterworth-Heinemann, Oxford, OX, Boston, MA; 1999.

[4] Herstatt, C., Verworn, B. Management der frühen Innovationsphasen: Grundlagen - Methoden - Neue Ansätze, 2nd edn. Betriebswirtschaftlicher Verlag Dr. Th. Gabler | GWV Fachverlage GmbH Wiesbaden, Wiesbaden; 2007.

[5] Kim, J., Wilemon, D. Focusing the fuzzy front–end in new product development 32; 2002. p. 269.

[6] Schwankl, L. Analyse und Dokumentation in den frühen Phasen der Produktentwicklung, München; 2002.

[7] Preece, J., Rogers, Y., Sharp, H. Interaction design: Beyond human-computer interaction. Wiley, New York, NY; 2002.

[8] Palomares, C., Franch, X., Quer, C., Chatzipetrou, P. et al. The state-of-practice in requirements elicitation: an extended interview study at 12 companies 26; 2021. p. 273.

[9] VDI e.V. Entwicklung technischer Produkte und Systeme: Gestaltung individueller Produktentwicklungsprozesse Blatt 2(2221); 2019.

[10] VDI e.V. Entwicklung technischer Produkte und Systeme: Modell der Produktentwicklung Blatt 1(2221); 2019.

[11] Schlegel, M., Pfaff, F., Rapp, S., Albers, A. Implications of Creating Solution Concepts Based on the Use of References 2; 2022. p. 781.

[12] Sivaloganathan, S., Shahin, T.M.M. Design reuse: An overview 213; 1999. p. 641.

[13] International Organization for Standardization (ISO). ISO/IEC 25010:2011 - Systems and software engineering - Systems and software Quality Requirements and Evaluation (SQuaRE) - System and software quality models, Genf, Schweiz.

[14] Wagenführ, A., Scholz, F., Editors. Taschenbuch der Holztechnik, 3rd edn. Fachbuchverlag Leipzig im Carl Hanser Verlag; 2018.

[15] Neuhaus, H. Ingenieurholzbau. Springer Fachmedien, Wiesbaden; 2017.

[16] Nestler, D.J. Beitrag zum Thema Verbundwerkstoffe - Werkstoffverbunde: Status quo und Forschungsansätze. mv Monsenstein und Vannerdat; Universitätsverlag Chemnitz, Münster, Chemnitz; 2014.

[17] Fleischer, J., Coutandin, S., Nieschlag, J. Einführung in intrinsische Hybridverbunde, in Intrinsische Hybridverbunde für Leichtbautragstrukturen, Springer, Berlin, Heidelberg; 2021. p. 1.

[18] Tochtermann, W., Bodenstein, F. Verbindungselemente, in Konstruktionselemente des Maschinenbaues, Springer Berlin Heidelberg, Berlin, Heidelberg; 1968. p. 65.

[19] Ivanov, I.V., Sadowski, T. Numerical modelling and investigation of plywood progressive failure in CT tests 45; 2009. p. 729.

[20] Piazza, G., Heyner, D.B., Beeh, E., Siefkes, T. Innovative usage and application-oriented simulation of veneer based hybrid materials in vehicle structures, Stockholm; 2021.

[21] Wang, B.J., Yu, C. Computer simulation model of hot-pressing process of LVL and plywood products; 2003.

[22] Susainathan, J., Eyma, F., Luycker, E. de, Cantarel, A., Castanié, B. Numerical modeling of impact on wood-based sandwich structures., Mechanics of Advanced Materials and Structures; 2019.

[23] Kellner, P., Rommelfanger, S., Schmidt, D. Holz-Kunststoff-Hybridbauteil(10 2022 122 808.8); 2022.

[24] Verband der Finnischen Forstindustrie. Handbuch über finnisches Sperrholz. Verband der finnischen Holzindustrie, Helsinki; 2001.