TOWARDS A HOLISTIC APPROACH TO INCREASE SUSTAINABILITY IN AIRCRAFT CABIN DESIGN

Sven Wehrend[1], Katharina Zumach[1], Lukas Schwan[1] & Dieter Krause[1]

[1]Hamburg University of Technology (TUHH), Institute of Product Development and Mechanical Engineering Design (PKT), Hamburg, Germany

Abstract

The aviation industry is facing the challenge of increasing sustainability requirements and targets. The cabin offers the opportunity to introduce short-term and medium-term sustainability improvements in existing aircraft fleets. In order to holistically address sustainability in the aircraft cabin, the three sustainability strategies of efficiency, consistency and sufficiency are considered in this article and addressed at both product architecture and component level. At the product architecture level, it is shown that modularization has great potential to improve sustainability along the entire product life cycle, but that there is a lack of methods for modularization strategies that contribute to the development of sustainable products. Therefore, it is shown which sustainability criteria and indicators can be addressed at the different levels of a product architecture. At the component level, there is a lack of comparisons of alternative lightweight materials and design alternatives with conventional designs and materials in terms of sustainability. Therefore, it is shown how the design of lightweight methods of construction can be combined with LCA by the example of conventional and bio-based flax sandwich structures when used in an aircraft cabin. The studies show the importance of a requirements-oriented design in terms of sustainability.

Keywords: sustainability, cabin, aviation, lightweight design, product architecture

1. Introduction

Global aviation is responsible for roughly 2% of the global CO_2 emissions while it is contributing around 4% of the world's gross domestic product [1]. Facing climate change, the aviation industry needs to become more sustainable. The European union therefore has set the goal to reduce CO_2 emissions by 75% until 2050 [2]. Due to average aircraft lifespans of 20-30 years, besides totally new aircraft and propulsion concepts, there is also a need to find solutions for reducing the emissions of the existing fleets. The aircraft cabin, which is responsible for 10-20% of an aircraft's overall CO_2 emissions, is one possibility to address existing fleets in short and medium terms [3]. As the cabin is replaced 4-5 times during an aircraft's life, improvements in the cabin are able to penetrate the active fleet faster than new aircraft concepts.

For a holistic approach, all three strategies of sustainability, efficiency, consistency and sufficiency are considered. Efficiency aims at a better, more productive use of the materials and raw materials used, for example through technical innovations. Consistency describes the search for and use of alternative materials that are better for the environment than those previously used. This also includes closing material cycles. Sufficiency is the third strategy that describes a reduction in the consumption of resources by questioning or reducing needs and consumption directly. For example, by questioning whether a defective product really needs to be replaced by a new one or whether it can be repaired or replaced by a used one. If these three sustainability criteria are applied to the aircraft cabin, consistency can be addressed by using bio-based materials instead of conventional fibre composite components. The improvement of lightweight design as a whole through new methods of construction and the associated reduction in emissions during the use phase can be assigned to efficiency. Sufficiency as the last strategy is addressed at the level of product architecture design. Here, the reparability and reusability of cabin equipment modules can be improved through a targeted, modular design.

Within the cabin, the sustainability can be improved at product architecture level fostering circular economy as well as on components level through lightweight design and alternative materials. In terms of the product architecture level, modularity offers benefits towards sustainability throughout the entire life cycle, but methods for modularization strategies that support achieving sustainable results regarding the entire life cycle are missing. Regarding lightweight design, especially with alternative materials, there is little work in the literature to date on the holistic evaluation of fibre composite components with alternative bio-based materials. This makes it extremely difficult, to evaluate different methods of construction at an early development phase, as the use phase regularly accounts for the largest share of a component's overall emissions in aviation. Therefore, in this contribution both levels, the product architecture level and the component level, are addressed to develop a holistic approach to increase sustainability in aircraft cabin design.

2. State of the Art

In addition to environmentally friendly product design, product development also has an impact on more environmentally friendly production (production phase), extended service life and useful life (use phase), ease of repair and ease of dismantling and recycling (disposal phase) [4]. The product development phase offers great potential for influencing the sustainability of a product throughout its life cycle, as this is when the key product characteristics are defined [5]. It is assumed that the influence on environmental impacts is analogous to the influence on costs in product development [6]. The aim should be to anticipate the impact on sustainability within the product life cycle early on in the development process, as the degree of product influence is greatest in these phases. Measures along the product life cycle phases should not be considered independently of each other, partly because they sometimes pursue opposing goals. Measures that initially generate higher expenditure or higher environmental impacts in the early phases (e.g. use of high-quality materials, modular design) can result in lower expenditure or lower environmental impacts in the course of the product's life (e.g. extended service life, ease of disassembly) [4]. It is therefore necessary to take into account all life phases regarding the sustainability.

Additionally, the assessment of a product's sustainability impact is oftentimes focused on the product itself, without taking into account the entire product family's variety and potentials that could be achieved with a combined perspective on sustainability and product variety [19]. Based on a systematic literature review, Sonego et al. [20] show that modularity offers benefits towards sustainability throughout the entire life cycle, but that further research is needed in order to identify modularization strategies that support achieving sustainable results regarding the entire life cycle. Therefore, a methodical approach to compare and realize sustainability potential lying within the rethinking and redesign of a product family's architecture is needed, so that different concepts can be compared in regards to their sustainability impact.

The selection of materials also focuses on the earlier development phases in which the product concept is defined. The environmental analysis of the product is usually carried out later on in the design and detailing phase of the design, in which the environmental impact and availability of raw materials are also assessed [7]. In terms of materials, composite materials in form of sandwich structures consisting of synthetic fibres and resin systems as well as light metals such as aluminium are mostly used in aircraft cabins [8]. Figure 1 summarises the most frequently used constituents for sandwich structures in aircraft cabins with their disadvantages regarding sustainability. On the one hand, the materials used must fulfil the aviation approval requirements, such as fire and smoke resistance [9], and on the other hand, low weight is essential, as 98-99 % of emissions are generated during the use phase [8],[10],[11],[12]. One problem with composite materials in terms of sustainability in general is the separation of constituents and components before they can be given into the recycling process [13],[14]. In addition, different types of fibre reinforcements and contamination with fillers, core materials, paints and inserts pose a challenge for recycling [8]. Glass fibres are mainly used for the face sheets, as they are inexpensive and still have good mechanical properties [15]. However, the production of synthetic fibres requires large amounts of energy. For example, the production of glass fibres requires around 45,6 MJ/kg and is also associated with considerable amounts of greenhouse gas emissions, as they are made from petrochemical raw materials [8]. In addition to the manufacturing phase, there is only limited interest in the recycling of glass fibres as they are comparatively inexpensive. Currently, the most popular method of recycling glass fibres prepregs at the end of its life cycle is to shred it and use it as a filler or as a fuel in cement production [8]. Aramid paper (meta-Nomex®) impregnated with phenolic resin is usually used for the honeycomb core [8]. As with glass fibres, aramid fibres are synthetic fibres that have similar disadvantages in terms of sustainability as the glass fibres described above. In the field of resin systems, phenolic resins based on thermosetting polymer matrices are primarily used for cabin monuments [8]. Due to the good temperature resistance and the low smoke and pollutant emissions of phenolic resins, they are mostly used for cabin monuments [8]. All thermosetting matrices used in aviation are obtained from monomers of fossil origin. The synthesis of the petroleum-based resin, the extraction and processing of which is associated with considerable environmental pollution, energy consumption and greenhouse gas emissions, is the most environmentally damaging component of composite materials. Furthermore, phenolic resins are often difficult to recycle. Due to the problems identified with the materials currently used, efforts are being made to replace them with bio-based materials, while the overall mechanical properties continuing to play a decisive role.

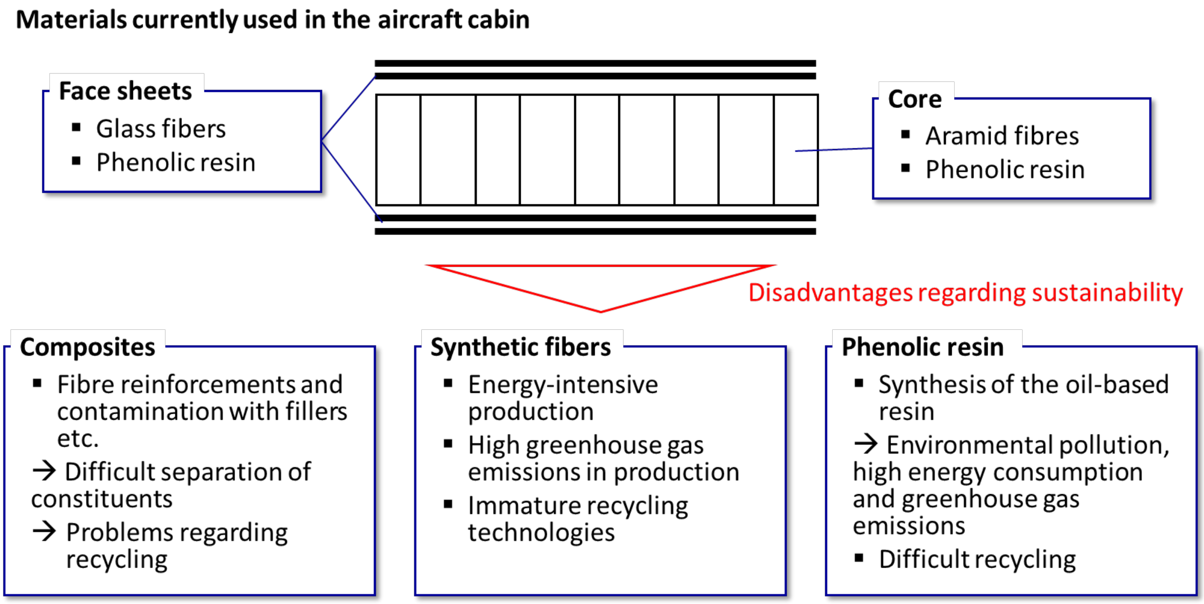

Figure 1: Materials currently used in the aircraft cabin and their disadvantages regarding sustainability

For the ecological evaluation of products, Life Cycle Assessment (LCA) has become an established tool. In LCA, a distinction is made between operational, process and product LCA with regard to the system boundary [16]. The product life cycle assessment refers to the entire product life cycle "from cradle to grave" of a product and is dealt with in ISO 14040 and ISO 14044 [17]. The LCA considers the environmental aspects and impacts associated with a product system. Economic and social aspects are not covered, but an LCA can be expanded to include these using the approaches and methods described in the standard [18]. According to the standard, the LCA consists of the four steps of defining the objective and the scope, life cycle inventory, impact assessment and evaluation, which are carried out iteratively [17], [18]. If the impact assessment step is omitted, the result is a Life Cycle Inventory Study (LCI Study) [18].

3. Potentials Lying within the Product Architecture of Modular Product Families

In order to analyse a product family's sustainability potential, criteria and indicators for sustainability need to be defined. This also serves for providing a common understanding of the term sustainability for all stakeholders within the sustainability assessment. In this contribution Hallstedt's [21] understanding of a criterion as a "target of a prioritized aspect or the level of the aspect that we strive for" and of an indicator as a "measurement or fact (qualitative or quantitative) that can indicate the state or level of the criterion" has been followed. After researching criteria and indicators, a final set of indicators to be analysed has been defined. Sorting them into the three dimensions of sustainability – social, economic and ecologic sustainability – and marking the life cycle phases that they apply to allows for a better understanding of the allocation of the indicators as we aim at covering all three dimensions.

When deciding on a modular product architecture, not all of the decided upon indicators are directly influenced by the product architecture itself. It is therefore necessary to cluster the indicators into two groups: those directly influenced by the modular product architecture and those only indirectly influenced by it. A modular product family consists of different variants that are formed with modules. Thereby, the modules are formed by clustering components. The components themselves are made from different materials. To completely assess the sustainability potential lying within the product architecture of a product family, those four levels – product variant, module, component and material – have to be taken into account. The criteria and indicators should therefore be assigned to the different levels of the modular product architecture (see Figure 2).

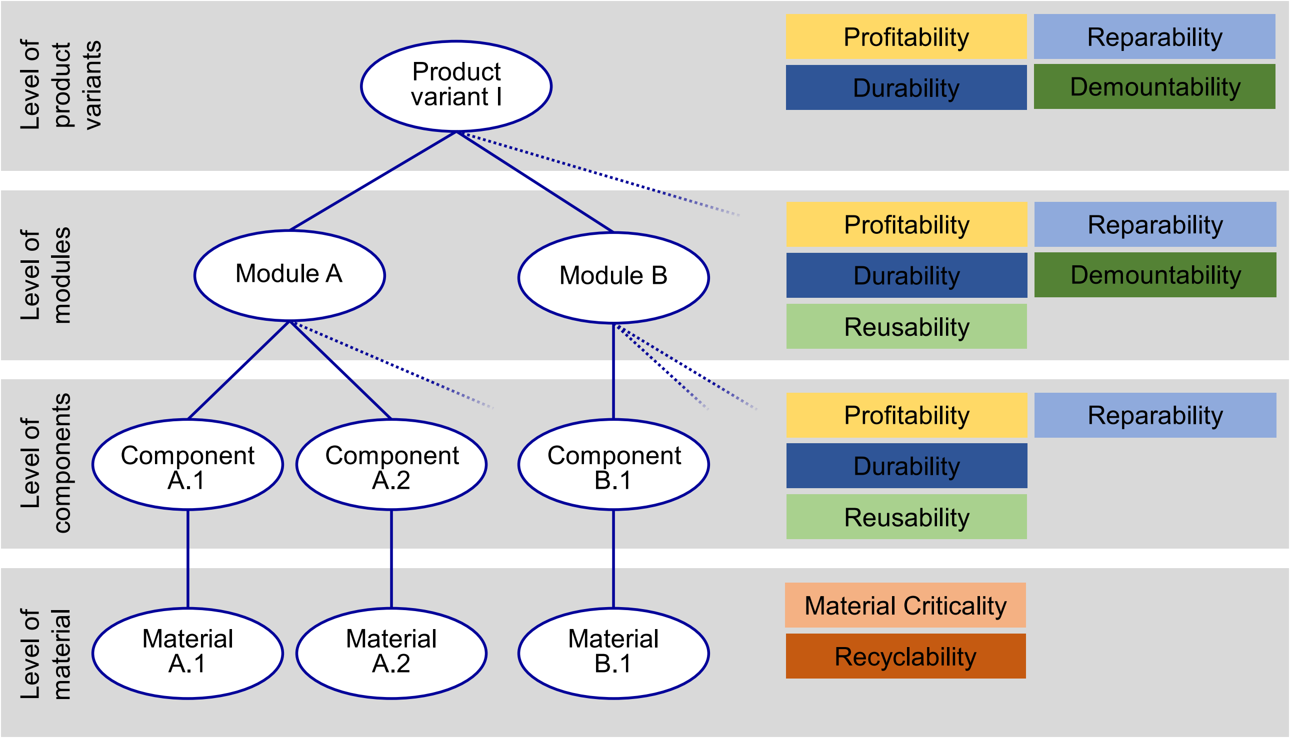

Figure 2: Sustainability criteria related to the modular product architecture

The different architectural levels of the product family are highlighted with grey boxes and within the levels the elements are shown as ellipses. Especially the levels of product variants and modules are the subject of consideration when designing modular product architectures. The criteria, represented as rectangles, can be assigned to the levels. It is to note that Figure 2 does not depict the indicators for the criteria as to not overload the illustration. For better traceability, criteria that can generally be evaluated and addressed on several levels are highlighted in colour.

Looking at the criterion reusability, for example, it can be seen, that both components as well as modules can be reinstalled in refurbished products. In other words, the criterion can generally be applied on both levels of the product family from an evaluation perspective. However, by anchoring the criterion reusability at module level, benefits can be derived from the clearly defined interfaces between modules. This helps reducing variant-induced complexity within the product family. As a result, individual components that are to be reusable should therefore be defined as modules in the module-building step.

To measure the criterion for a product, an indicator is needed as described above. For example, Cerdan et al.'s [22] indicator "reusable parts" can be applied to the context of the product family and determine the weight of the modules that can be reused relative to the weight of the product. For existing product families, the weight of the product is known and thus, different product variants can be compared with each other. At an early conceptual stage where the product family is not yet defined, the weight of the modular product architecture concepts can only be estimated. Nonetheless, different concepts can already be compared using the assumptions.

As shown in Figure 2, a multitude of criteria, and therefore a possibly even higher number of indicators can be found for assessing the sustainability of a modular product architecture. The illustration thereby is concentrated on aspects that are influenced by the definition of the product architecture. Taking into account the indicators found that are only indirectly influenced by it, the list of indicators is even longer as those indicators should be taken into account in the subsequent in-depth elaboration of the concepts. The different indicators can influence each other, in the one hand side positively, but on the other hand negatively. Therefore, a procedure is required to weigh up any conflicting objectives when selecting concepts. One way of supporting this is by prioritizing the indicators. Should target conflicts arise while measuring the indicators, this helps finding the prioritized solution.

Since the aircraft cabin is made up of different monuments, a reference system is picked for the initial development of the approach. The reference system is defined as a product family of lavatories and thus the existing product family is analysed in regard to its variety and to the defined indicators. Based on this, components within the product architecture can be identified that need to be changed in order to decrease internal product variety and increase sustainability. With the components, optimized in regards to Design for Variety and their sustainability impact, modules are created. The formation of modules should thereby not only be based on a functional view but also on product strategic aspects that can be implemented through the use of module drivers. To exploit the sustainability potential of the product family, the modularization should therefore be conducted according to sustainable module drivers. Breimann et al. [23] present an exemplary list of possible module drivers associated to R-imperatives, that is taken into account. The developed module concepts can be reassessed using the selected indicators and according to the prioritisation of indicators the most sustainable concept is chosen to be implemented. Once a sustainable product architecture concept has been selected, sustainability can then be addressed as part of the design at component level, which is discussed in the next section.

4. Potentials in biobased lightweight design on component level

The aim of this paper is to contribute to a simpler evaluation of lightweight methods of construction with regard to sustainability. For this purpose, four different sandwich structure design concepts are designed for a 4-point bending test and a given design space and compared in terms of sustainability over the entire life cycle when used in an aircraft cabin. The sustainability is assessed by means of an LCA using the software Umberto, the Ecoinvent database and existing literature.

4.1 Design of different lightweight methods of construction

In order to overcome the problems of currently used materials with regard to sustainability as described in the state of the art, alternative materials for the use in the cabin were identified through systematic literature research. The literature lists various alternative materials and processes for use in aircraft cabins, such as thermoplastic resin systems or recycled carbon fibres, but the focus of this work is on bio-based materials. In addition to fulfilling the strict certification requirements of the aviation industry, the mechanical parameters have a decisive influence on suitability as a lightweight design material. Bio-based resins from natural resources exist to replace conventional oil-based resin systems. As they are of natural origin and abundantly available compared to oil-based raw materials, these materials have a significant potential for a more sustainable production of cabin monuments and a combination of glass fibres with bio-based resin systems can thus be a first way towards an introduction of partially bio-based composites. Due to the low lightweight design potential of the resin systems compared to the fibres, these are not analysed further with regard to their mechanical properties. Natural fibres can be seen as a potential alternative to synthetic fibres due to their high strength-to-weight ratio, their low cost and their biodegradable properties. Based on the literature analysed, Table 1 has been created showing the identified natural fibres and their mechanical properties. However, natural fibres also have disadvantages, such as fluctuating properties (e.g. due to dependence on weather conditions), high moisture absorption, incompatibility with many resin systems and easy flammability. To overcome these disadvantages, natural fibres must be chemically treated before being used in composite production.

Table 1: Natural fibers with mechanical properties identified through systematic literature research

Fibre type	Origin	Diameter (µm)	Length (mm)	Density (g/cm^3)	Tensile strength (MPa)	E-Modulus (GPa)	Elong. (%)	Literature
Abaca	Leaf	-	-	1.5	480-813	31.1-33.6	2.9-10	[8],[13]
Bagasse	Grass	-	-	0.89-1.25	155-350	17-22.05	5.5	[24]
Bambus	Grass	25-330	-	0.6-1.25	216.5-470	11-29	1.3-3.1	[13],[24]
Banana	Leaf	50-250	-	1.35-1.4	355-914	12-33.8	2.6-7	[13],[24]
Coir	Fruit	10-460	20-150	1.15-1.25	131-220	4-6	15-40	[8],[13],[25]
Cotton	Seed	10-45	10-60	1.5-1.55	400-543.5	9.05-12	3-10	[8],[13],[24],[25]
Flax	Bast	12-600	5-900	1.4-1.5	800-1500	18-80	1.2-2.95	[8],[13],[24],[25]
Hanf	Bast	25-500	5-55	1.45-1.55	550-900	35-70	1.6-4	[8],[13],[24],[25]
Jute	Bast	20-350	1.5-120	1.31-1.48	393-680	13-26.5	1.16-1.8	[8],[13],[25]
Kenaf	Stem	70-250	-	1.2-1.5	284-930	21-60	1.6	[13],[24]
Nettle	Bast	-	-	1.51	650	38	1.7	[13]
Ananas	Leaf	-	-	1.2-1.74	413-1627	60-82	2-14.5	[13],[24]
Ramie	Bast	20-80	900-1200	1.28-1.5	445-700	24.5-94.7	2-4.6	[8],[13],[24],[25]
Sisal	Leaf	8-300	900	1.3-1.5	390-680	12-41	2.3-2.5	[8],[13],[24],[25]
Softwood	Wood	-	-	1500	1000	40	-	[13]
Hardwood	Wood	-	-	1200	950	37.9	-	[13]
Harakeke	Leaf	-	4-5	1.3	440-990	14-33	4.2-5.8	[25]
Alfa	Grass	-	350	1.4	188-308	18-25	1.5-2.4	[25]
Silk		-	Cont.	1.3	100-1500	5-25	15-60	[25]
Wool	Animal	-	38-152	1.3	50-315	2.3-5	13.2-35	[25]
E-glass		5-24	∞	2.55-2.6	1900-3500	63-85	1.8-4.5	[8],[13],[26]

Based on the material properties determined, it is evident that flax fibres have a high potential compared to other natural fibres, which is why this type of natural fibre is considered further in this article. In addition to the mechanical properties, which have a direct influence on the subsequent component weight and thus the emissions in the use phase, emissions are also emitted in the other life phases. In order to be able to make further statements about the potential of ecological lightweight materials with regard to sustainability, a combined analysis of lightweight design and life cycle assessment was carried out to estimate the potential of flax fibres. As sandwich structures are primarily used in the current cabin, the potential analysis is also carried out with sandwich structures at structural element level.

The aim of the investigation is to conduct a product-independent analysis in order to be able to make generic statements regarding the potential of the corresponding sandwich design. The 4-point bending test with an upper support spacing of 60 mm, a lower support spacing of 180 mm and a support diameter of 10 mm is therefore selected as a generic comparative test for the design. In addition to a reference panel with conventionally used materials, four different panel alternatives with flax fibre constituents were considered. In addition to replacing the face sheets, a core alternative was also investigated in which a fold core made of flax fibres is used. The influence of a coarse-meshed flax fibre fabric to increase the bending stiffness, like the so-called powerRibs™ from Bcomp [29], which is attached to the outside of the face sheets, was also investigated.

The analysed sandwich structures are summarised in Figure 3. The core height of the various panels was kept constant at 20 mm during the design and only the number of face sheets was varied. The length of the samples was set at 250 mm in each case, while the width of the samples was 50 mm. The design was carried out numerically using the FEM software Abaqus/Explicit, whereby the number of face sheets was successively increased for each panel alternative. The maximum force and the stiffness were determined from the respective force-displacement diagram, which is also shown in Figure 3. The material parameters for the simulation of the conventional sandwich materials were taken from Seemann [30], whereby the core was modelled as a 3D continuum model. Data sheets from the manufacturer Bcomp [31] were used for the flax constituents. As the flax fibre fold core is still under development, no valid material data was available. The mechanical properties of the Nomex® honeycomb core were therefore adopted, whereby the mechanical influence of the core is assumed to be low in the selected design case. However, the influences on the other life phases of the new flax fibre fold core can be considered in the subsequent life cycle assessment.

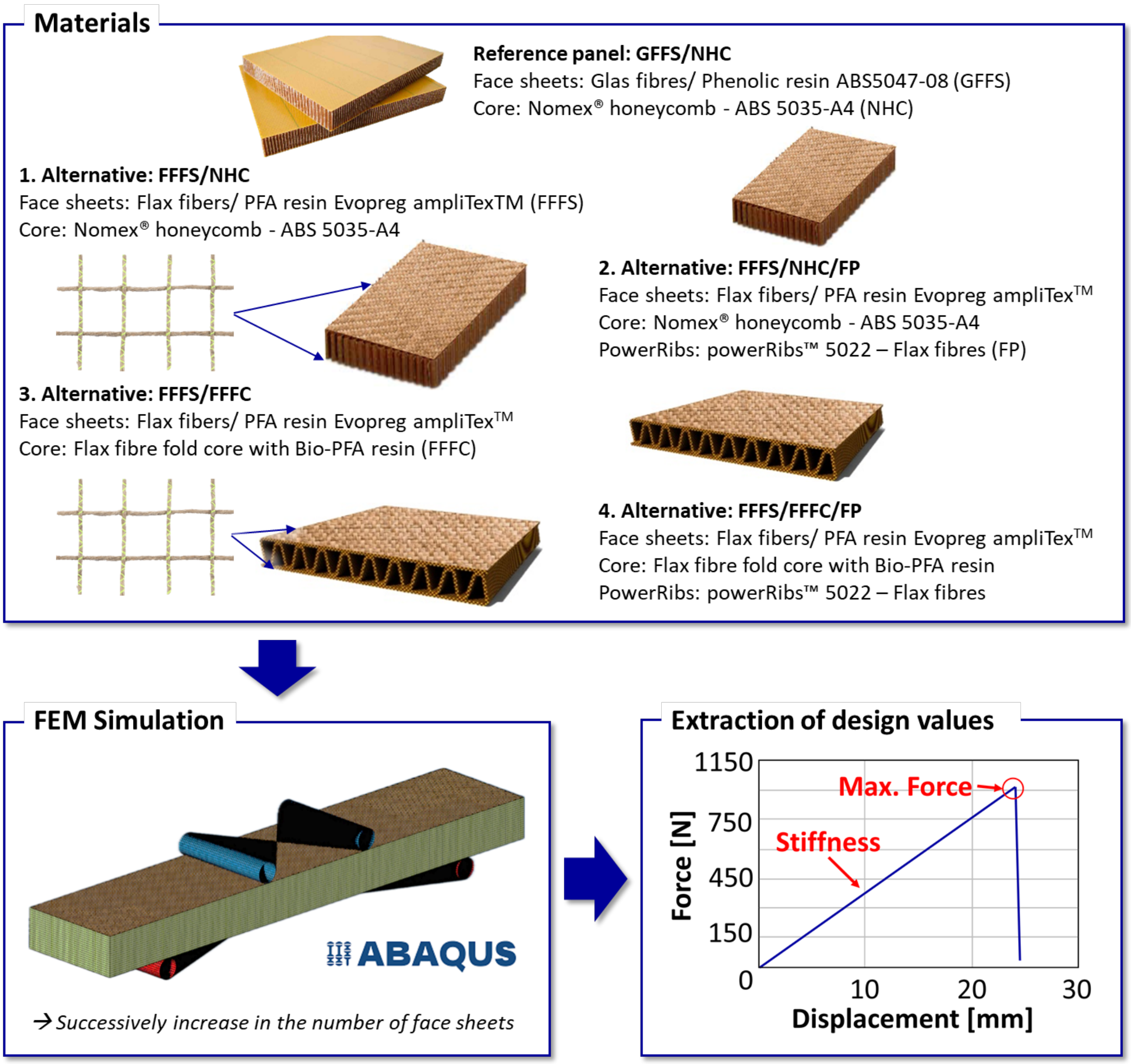

Figure 3: Selected sandwich configurations for the design (top), FEM model of the 4-point bending test (bottom left) and exemplary force-displacement diagram (bottom right)

The maximum forces and stiffnesses determined for the different sandwich configurations and number of face sheets have been converted into a diagram, which is shown in Figure 4. After specifying a required force and minimum stiffness, the diagram can be used to directly determine the number of face sheets required for the respective sandwich configuration. For the example in the figure, where a minimum force of 1200 N and a minimum stiffness of 600 N/mm is required, this means that five face sheets are required for the reference panel, while three face sheets would be required for the first and third alternatives and only two face sheets for the second and fourth alternatives. This information from the design serves as input for the life cycle assessment.

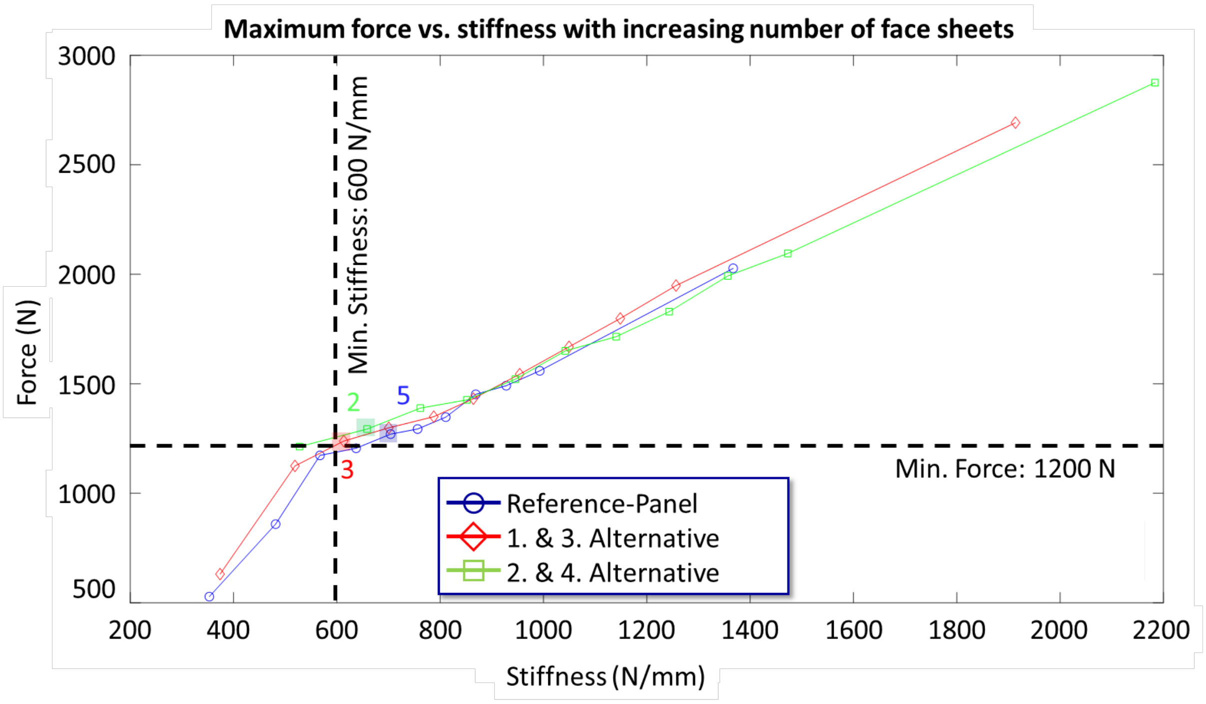

Figure 4: Maximum force-stiffness diagram of the designed sandwich panels for different numbers of face sheets

4.2 Life cycle analysis

The aim of the life cycle assessments carried out is to compare different sandwich panels (comparative life cycle assessment). As this comparison is to be made holistically, taking into account the complete life cycle, a cradle-to-grave approach is pursued (cf. [17]). For the different designs, in addition to the production of the respective panels, raw material production, transportation routes between the various life phases, the use phase and disposal at the end of the service life are taken into account. Figure 5 shows an example of the system boundaries for the reference panel. For the overarching goal of general assessability of different designs for aviation even at the concept stage, the standardized load case of a bending beam is taken into account. In order to take into account the aviation-specific high influence of the use phase, the functional unit is the fictitious use of each investigated bending beam as part of an aircraft cabin element. For this purpose, use over 7 years with a total of 20800 medium-haul flights is assumed. As these are simple structural components, no maintenance and servicing activities are assumed.

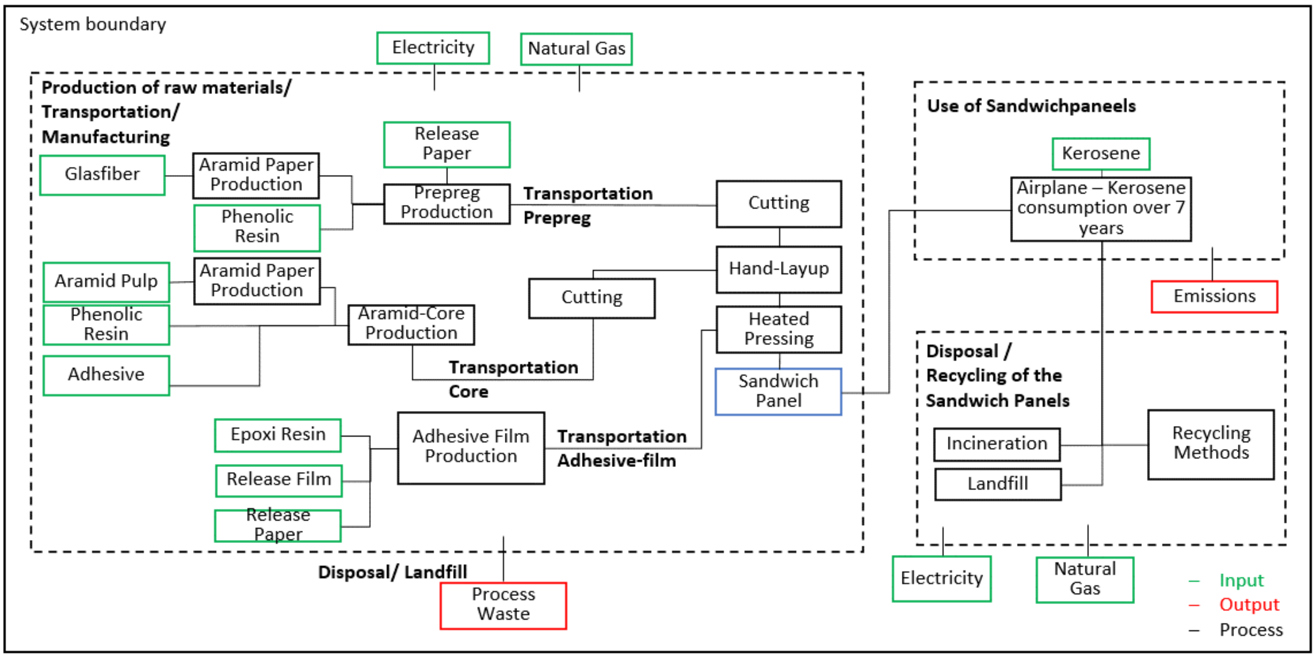

Figure 5: System boundaries for the reference panel

The "Global Warming Potential" (GWP) indicator of the Intergovernmental Panel on Climate Change (IPCC) is used to estimate the impact of emissions [32]. This indicates the impact of anthropogenic emissions on climate change. For this purpose, the climate impact of different greenhouse gases (GHG) is compared with that of the reference gas carbon dioxide (CO_2), thus enabling a conversion into CO_2 equivalents. However, as gases have different residence times in the atmosphere, the time period under consideration also has an influence. The IPCC provides for a determination of the GWP for 20, 100 and 500 years, whereby 100 years is the most common time horizon and is also used in DIN EN ISO 14067, and is also used accordingly in this contribution.

As some of the design concepts investigated are new, alternative materials, research and assumptions regarding the production of the materials and manufacturing are required in order to draw up the life cycle inventory, as there is no existing industrial production process in the area of alternative concepts that is comparable to that of the reference panel. For this reason, it was assumed that the bending beams were manufactured in the TUHH laboratories. Some raw material data could be obtained directly from the Ecoinvent database (e.g. glass fibers); for other materials, e.g. aramid fibers or the bio-based PFA resin, the Ecoinvent database did not contain any data, meaning that other, similar processes or the research of values from existing literature had to be used. Contact was also made with manufacturers. However, as the alternative materials are still in the development stage, it was not possible to obtain any specific values regarding life cycle assessments or production in this way either.

4.3 Results

The results of the life cycle assessment for the load case examined, as can be seen in Figure 6, indicate that the conventional reference panel consisting of glass fiber facings, an aramid honeycomb core and phenolic resin has the highest GWP-100. The two alternative design concepts with flax fiber face sheets (abbr. FD) and aramid honeycomb core (abbr. NW) or flax fiber fold core (abbr. FF) each show a GWP-100 of 95% of the reference panel. The two combinations with an additional layer of flax fiber power ribs (abbr. FP) perform even better with a GWP-100 of 82% and 81% of the reference panel respectively.

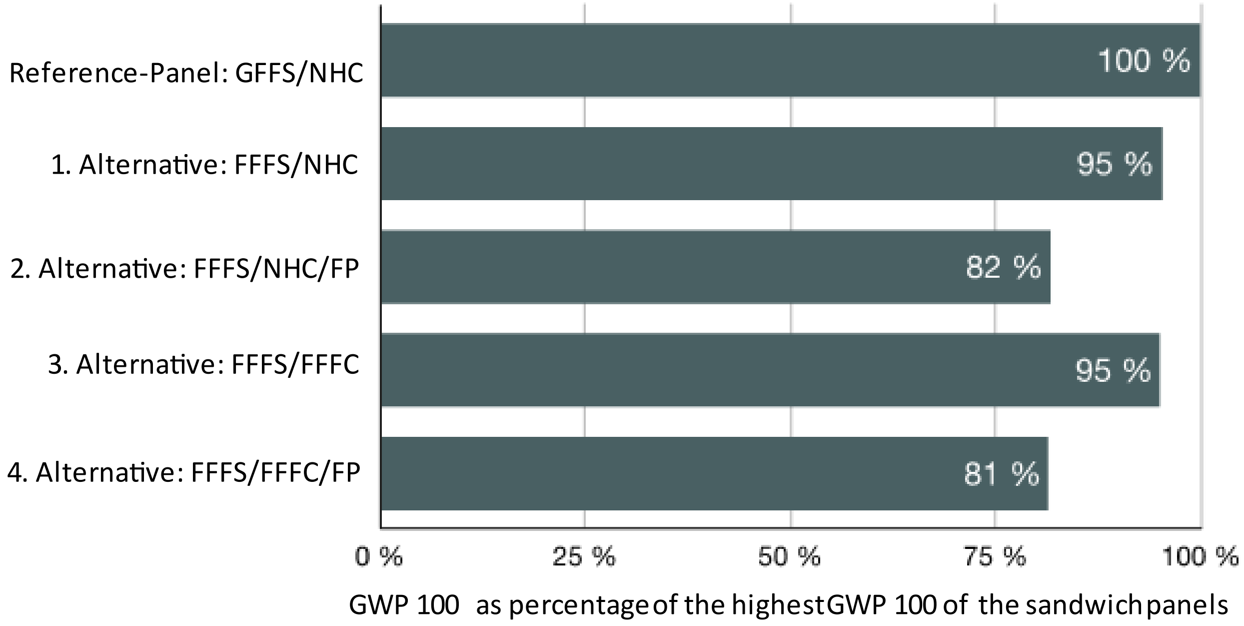

Figure 6: Comparison of the Overall GWP of the different alternatives

In order to take account of the current plans for climate-neutral flying by 2050, the impact of using sustainable aviation fuel (SAF) on the use phase was also investigated. SAF is aviation fuel that can be burned in conventional engines but is produced from biological raw materials such as biomass and waste products. Combustion therefore still produces CO_2, but this is biogenic CO_2 that was previously removed from the atmosphere to produce the fuel and does not come from fossil sources.

The ReFuelEu initiative [33] proposes a mandatory admixture of SAF at major EU airports. According to this, the SAF share is to be increased to 63% by 2050. Accordingly, the impact of SAF shares of 63% and 100% on the GWP of the utilization phase was investigated (see Figure 7).

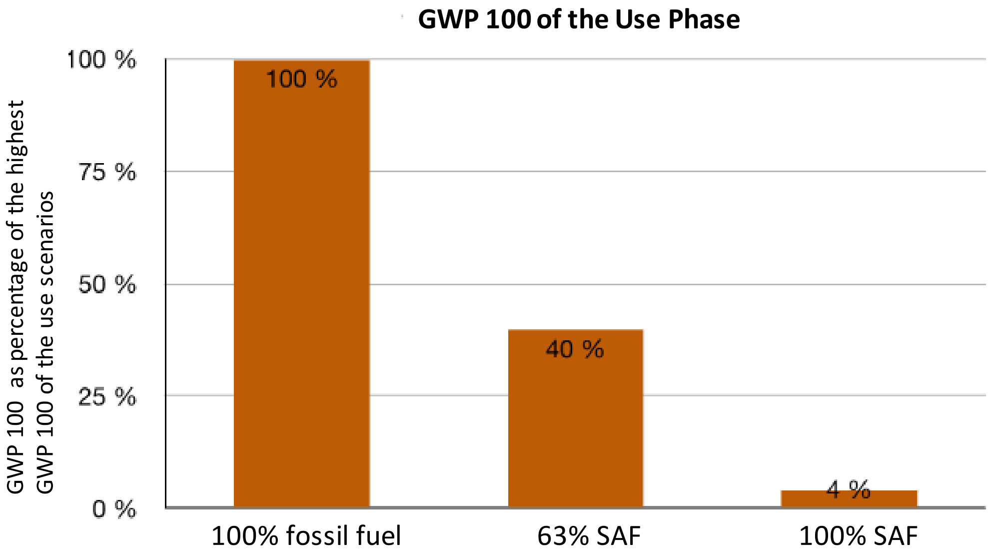

Figure 7: GWP of the use phase for different SAF shares

Here it can be seen that a share of 63% may lead to a reduction in use-phase emissions to around 40 percent, whereas the use of 100 % SAF might lead to a reduction of the emissions down to 4 percent under very positive assumptions. However, it should be noted that the savings achieved through SAF depend very much on the respective manufacturing process of the SAF and that there is a wide range here. In summary, it can be stated that no general statement regarding a more sustainable design is possible at this point in time. This is mainly due to the major influence of the utilization phase and thus the weight, even assuming an SAF rate of 100%. Figure 8 compares the GWP value of the various design concepts for two different load cases.

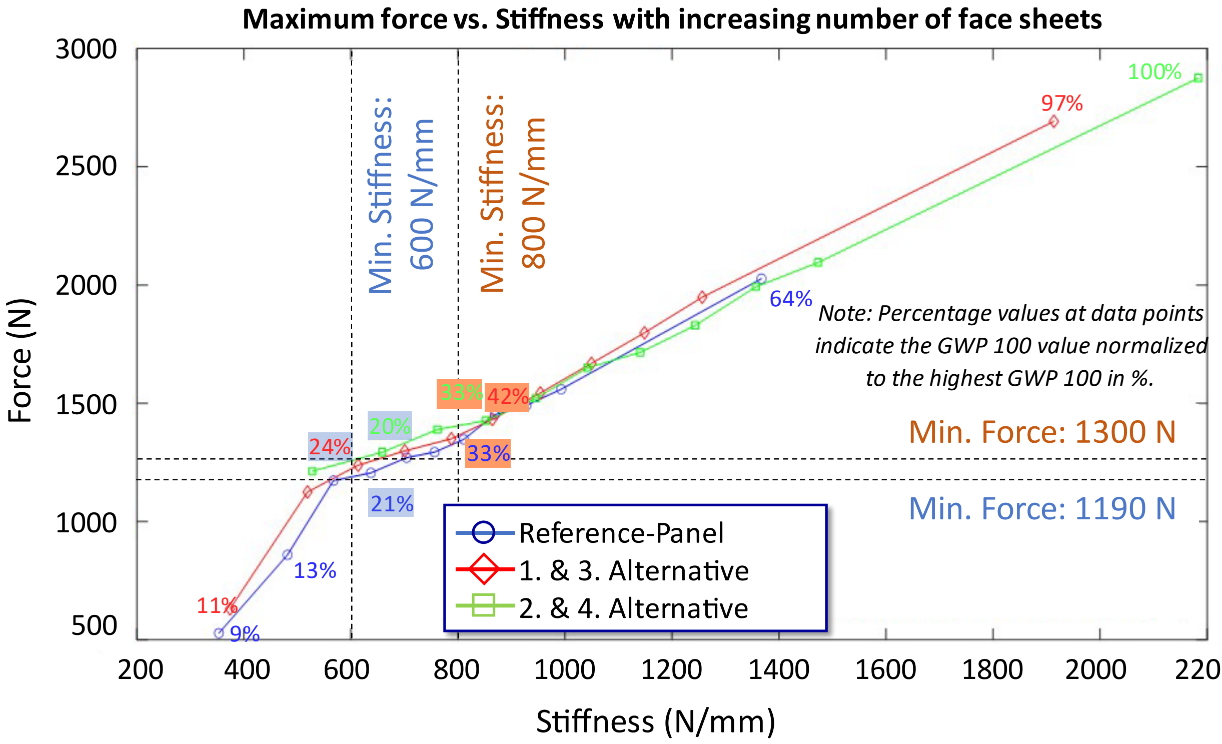

Figure 8 : relative GWP as percentage of maximum value of the designed sandwich panels for different numbers of face sheets

It is easy to see here that, depending on the respective design point, different design concepts can be the most sustainable. In this case, this is based on the fact that a different concept is the lightest in each case, as the threshold values above which an additional cover layer and therefore more weight is required are at different loads.

5. Conclusion and Outlook

In this contribution an approach to the development of sustainable aircraft cabin components and modules is presented. For a holistic approach, sustainability is addressed both at the level of individual components and at the product structure level. Concerning the product structure-level it is shown that modular product structures offer the possibility to improve sustainability. The paper shows steps towards comparing different product architecture concepts in regards to their sustainability impact, but there is still work to be done to better understand the potentials and impacts modularisation can have on sustainability. Concerning the component-level different lightweight designs are presented, designed and simulated in a 4-point bending test and compared in terms of sustainability by means of an LCA. The results show the importance of a detailed design due to the major influence of weight in the use phase. Therefore, physical coupon and bending tests on the flax-fibre based materials must be performed in order to improve the design of the bio-based materials and make conclusions regarding their sustainability. Merging the results of both levels, the product architecture and the component level, contributes towards a holistic approach to increase sustainability in aircraft cabin design. An exciting and open research question in this context is how the information from the specific component design can be used as a sustainability module driver in the modularization, which is carried out in early development phases. The inclusion and evaluation of other sustainability criteria in addition to the LCA additionally results in conflicting objectives in early development phases, which can be overcome using suitable methods, such as multi-criteria decision-making (MCDM) methods. However, the weighting and comparability of the different sustainability criteria remains a challenge in the area of aircraft cabins, which must be addressed in terms of research.

6. Acknowledgements

The presented research is based on the results of the project “RECab - Resource Efficient Cabin (FKZ: 20K2103E)” and is funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) as part of the sixth Civil Aeronautics Research Program (LUFO VI-2).

7. Contact Author Email Address

mailto: sven.wehrend@tuhh.de

8. Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

9. References

[1] Aerospace, Security and Defence Industries Association of Europe. *2022 Facts & figures*. Accessed 21 November 2023, https://www.asd-europe.org/sites/default/files/2022-11/ASD_Facts%20%26%20Figures%202022.pdf

[2] European Commission, Directorate-General for Mobility and Transport, Directorate-General for Research and Innovation. *Flightpath 2050 – Europe's vision for aviation – Maintaining global leadership and serving society's needs.* Publications Office, 2011, https://data.europa.eu/doi/10.2777/50266

[3] BDLI – German Aerospace Industries Association*. The role of cabin and cargo for sustainable aviation*. Accessed 21 November 2023,

[4] Walther, G.: *Nachhaltige Wertschöpfungsnetzwerke. Überbetriebliche Planung und Steuerung von Stoffströmen entlang des Produktlebenszyklus*, Wiesbaden: Gabler Verlag, GWV Fachverlage GmbH, 2010.

[5] Ponn J. and Lindemann U. *Konzeptentwicklung und Gestaltung technischer Produkte. Systematisch von Anforderungen zu Konzepten und Gestaltlösungen*. 2nd edition, Springer-Verlag, 2011.

[6] Herrmann C. *Ganzheitliches Life Cycle Management*. Springer, 2010.

[7] Giudice, F., La Rosa, G., Risitano, A. Materials selection in the life-cycle design process: a method to integrate mechanical and environmental performances in optimal choice, *Materials and Design*, Vol. 26 Issue 1, pp 9-20, 2005. https://doi.org/10.1016/j.matdes.2004.04.006

[8] Bachmann, J., Hidalgo, C., Bricout, S. and Saul: Environmental analysis of innovative sustainable composites with potential use in aviation sector—A life cycle assessment review*, Sci China Tech Sci,* Vol. 60, pp 1301–1317, 2017, https://doi.org/10.1007/s11431-016-9094-y

[9] Eli, M.P. *Fire- and Smoke-Resistant Interior Materials for Commercial Transport Aircraft*, Committee on Fire and Smoke Resistant Materials for commercial Aircraft interiors, Washington, 1995

[10] Gomez-Campos, A., Vialle, Claire., Rouilly, Antoine., Hamelin, L., Rogeon, A., Hardy, D.,Sablayrolles, C. Natural Fibre Polymer Composites – A game changer for the aviation sector? *Journal of Cleaner Production*, Volume 286, 2021, https://doi.org/10.1016/j.jclepro.2020.124986

[11] Vidal, R., Moliner, E., Martin, P.P., Fita, S., Wonneberger, M., Verdejo, E., Vanfleteren, F., Lapena, N., Gonzalez, A. Life Cycle Assessment of Novel Aircraft Interior Panels Made from Renewable or Recyclable Polymers with Natural Fiber Reinforcements and Non-Halogenated Flame Retardants. *Journal of Industrial Ecology, Vol. 22, Issue 1, pp 132-144, 2018.* https://doi.org/10.1111/jiec.12544

[12] Bachmann J, Yi X, Tserpes K, Sguazzo C, Barbu LG, Tse B, Soutis C, Ramón E, Linuesa H, Bechtel S. Towards a Circular Economy in the Aviation Sector Using Eco-Composites for Interior and Secondary Structures. Results and Recommendations from the EU/China Project ECO-COMPASS. *Aerospace*. 2021; 8(5):131. https://doi.org/10.3390/aerospace8050131

[13] Atmakuri A, Palevicius A, Vilkauskas A, Janusas G. Review of Hybrid Fiber Based Composites with Nano Particles—Material Properties and Applications. *Polymers*. 2020; 12(9):2088. https://doi.org/10.3390/polym12092088.

[14] Kek T, Potočnik P, Misson M, Bergant Z, Sorgente M, Govekar E, Šturm R. Characterization of Biocomposites and Glass Fiber Epoxy Composites Based on Acoustic Emission Signals, Deep Feature Extraction, and Machine Learning. *Sensors*. 2022; 22(18):6886. https://doi.org/10.3390/s22186886

[15] Jerrin, T.V., N.S. Sarath, R., Godwin, J. Development of biodegradable composites and investigation of

mechanical behaviour, *Materials Today: Proceedings*, Volume 38, Part 5, Pages 3378-3385, 2021 https://doi.org/10.1016/j.matpr.2020.10.478

[16]Herrmann, C.: *Ganzheitliches Life Cycle Management. Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen*. 1., Heidelberg: Springer-Verlag, 2010

[17]Klöpffer, W., Grahl, B. *Life Cycle Assessment (LCA) A Guide to Best Practice*, Wiley, 2014

[18]ISO – INTERNATIONAL STANDARD: ISO14040: Environmental management – Life cycle assessment – Principles and framework, 2006.

[19]Kim S., Moon S. K. Sustainable platform identification for product family design. *Journal of Cleaner Production,* Vol. 143, pp 567-581, 2017.

[20]Sonego M., Echeveste M., and Debarba H.. The role of modularity in sustainable design. A systematic review. *Journal of Cleaner Production*, Vol. 176, pp 196-209, 2018.

[21]Hallstedt S.. Sustainability criteria and sustainability compliance index for decision support in product development. *Journal of Cleaner Production*, Vol. 140, pp 251-266, 2017.

[22]Cerdan C., Gazulla C., Raugei M., Martinez E., Fullana-i-Palmer P. Proposal for new quantitative eco-design indicators: a first case study. *Journal of Cleaner Production*, Vol. 17, pp 1638-1643, 2009.

[23]Breimann R., Rennpferdt C., Wehrend S., Kirchner E. and Krause D. Exploiting the sustainability potential of modular products by integrating R-Imperatives into product life phases. *Proceedings of the International Conference on Engineering Design (ICED23)*, Bordeaux, pp 1785-1794, 2023.

[24]Debanan, B., Dhar, N.R. Selection of the natural fiber for sustainable application in aerospace cabin interior using Fuzzy MCDM model, Materialia, Vol. 21, 2021. https://doi.org/10.1016/j.mtla.2021.101270

[25]Pickering, K.L., Aruan Efendy, M.G., Le, T.M. A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing*, Vol. 83, pp 98-112, 2016 https://doi.org/10.1016/j.compositesa.2015.08.038

[26]Arockiam, N., Mohammad, J., Naheed, S. Sustainable bio composites for aircraft components. *Sustainable Composites for Aerospace Applications*, 2018. https://doi.org/10.1016/B978-0-08-102131-6.00006-2

[27]Heyden E., Hartwich T., Schwenke J. and Krause D.. Transferability of boundary conditions in testing and validation of lightweight structures. *30. DS 98: Proceedings of the 30th Symposium Design for X (DFX 2019)*, pp 85-96, 2019.

[28]Department of Defense. Composite materials handbook. Volume 3. Polymer matrix composites materials usage, design, and analysis. Department of Defense, 2002.

[29]Bcomp. powerRibs - Natural fibre reinforcement grid for high performance. Accessed 15 May 2024, https://www.bcomp.com/products/powerribs/

[30]Seemann R. A Virtual Testing Approach for Honeycomb Sandwich Panel Joints in Aircraft Interior. Berlin: Springer Berlin Heidelberg; 2020.

[31]Bcomp. *Sustainable Lightweighting to Decarbonise the World*. Accessed 15 May 2024, https://www.bcomp.com/

[32]Intergovernmental Panel on Climate Change (IPCC) (2023) 'Annex VII: Glossary', in *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 2215–2256.

[33]Soone, J.: "ReFuelEU Aviation initiative Summary of the Commission proposal and the Parliament's draft committee report", EPRS | European Parliamentary Research Service, 2022.