Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 136 (2025) 594–599

www.elsevier.com/locate/procedia

35th CIRP Design 2025

Procedure for the multi-objective design and sustainability optimization of composite sandwich structures in aircraft cabin applications

Lukas Schwan[a,*], Katharina Zumach[a], Sven Wehrend[a], Johann Schellhorn[a], Dieter Krause[a]

[a]*Hamburg University of Technology, Am Schwarzenberg-Campus 1, 21073 Hamburg, Germany*

* Corresponding author. Tel.: +49-40-42878-2661; *E-mail address:* lukas.schwan@tuhh.de

Abstract

In engineering, optimizing products across multiple performance metrics - such as cost, weight, and environmental sustainability - presents a significant challenge. Composite sandwich structures, in particular, offer a vast design space with diverse materials and geometric parameters, leading to conflicting design objectives. This study presents a procedure integrating Genetic Algorithms (GA), Finite Element Analysis (FEA), and rule-based performance metric calculations to address these challenges. GA facilitate efficient exploration of the design space, while via FEA mechanical performance is evaluated, and via rule-based calculations economic and ecological metrics are assessed. The procedure is applied to an aircraft partition-like sandwich structure, demonstrating its effectiveness in balancing trade-offs and achieving holistic design optimization. This approach provides valuable tools and insights for engineers and designers working with advanced composite materials, highlighting its potential to support sustainable development and informed decision-making in product design.

Keywords: Multi-objective optimization; Lightweight design optimization; Sandwich structure; Sustainable design

1. Introduction

In product development, a primary objective is to create products that satisfy specified requirements while excelling in performance metrics such as cost, weight, and sustainability. Consequently, optimizing these Key Performance Indicators (KPIs) is a central focus in this field [1]. However, in practice, it is often not feasible to maximize all target objectives simultaneously. This challenge arises because various design choices can have contradictory effects on the defined goals, necessitating compromise solutions in the final design [1]. This effect is particularly evident in the pursuit of sustainability, which is built upon three interconnected dimensions: ecological, economic, and social [2]. Each dimension includes numerous sustainability criteria and indicators that are closely linked to the United Nations' seventeen Sustainable Development Goals (SDGs) [3]. Indicators such as CO_2 emissions, the Social Progress Index, and costs are frequently employed to evaluate a product's sustainability. To comprehensively assess sustainability impacts across a product's entire life cycle, these indicators should be thoroughly calculated [4]. A variety of tools and data sources facilitate this analysis. For instance, Life Cycle Analysis (LCA) is a widely adopted method for determining the ecological sustainability of a product by for instance calculating the equivalent CO_2 emissions throughout its lifecycle [5,6]. Similarly, Life Cycle Costing (LCC) serves as a tool to evaluate economic sustainability by computing the accrued costs over the product's lifecycle [7]. The examples illustrate the broad spectrum of sustainability indicators, underscoring how the diversity of performance metrics often results in conflicting objectives. This complicates finding solutions that positively impact all metrics, leading to compromise solutions. In light of the previously discussed challenges and trade-offs involved in achieving sustainability goals, the aviation industry serves as an example of how sectors respond to the urgent demands of climate change. Facing the threat of climate change, the aviation industry is striving to

10.1016/j.procir.2025.08.102

become more sustainable. The global aviation sector is responsible for approximately 2% of the worldwide CO_2 emissions, while contributing around 4% to the global gross domestic product [8]. In response, the European Union has set a target to reduce CO_2 emissions by 75% by 2050 [9]. Since 95-99% of an aircraft's emissions occur during the use phase [10-12], lightweight design is crucial in mitigating environmental impact. The overall weight of the aircraft structure is closely linked to energy consumption and CO_2 emissions during this phase [13]. Given the average aircraft lifespan of 20–30 years, there is also a need, besides developing entirely new aircraft and propulsion concepts, to find solutions for reducing emissions of existing fleets. The aircraft cabin, accounting for 10–20% of an aircraft's total CO_2 emissions, presents a viable short- and medium-term opportunity for addressing sustainability in existing fleets [14]. Since the cabin is replaced 4–5 times over the life of an aircraft, improvements in this area can be integrated into the active fleet more quickly than new aircraft concepts. Within the aircraft cabin, lightweight design plays a crucial role and the use of sandwich structures has established due to their excellent specific strength and favourable bending properties. Typically, honeycomb cores made from Nomex® - a phenolic resin impregnated aramid paper - are utilized, paired with a glass fibre reinforced plastics (GFRP) face sheet [15]. Despite the weight advantages, these lightweight solutions often incur higher costs, and the materials used may pose environmental challenges during production and recycling [10-12]. To tackle these issues, there is growing interest in alternative, bio-based materials like flax or ramie for the use in aircraft cabins [10-12]. Although these materials may have slightly lower strength and stiffness properties compared to conventional ones, they provide a viable alternative. The variety of materials, combined with geometric design parameters such as core height and face sheet thickness, and the resulting combinatory variety significantly expand the design space. These factors, which highlight the vast design space and conflicting objectives, increase the challenges in developing sandwich structures for aircraft cabin applications.

In order to resolve the conflict of objectives, in the literature multi-objective optimization techniques, particularly Genetic Algorithms (GAs) are often used. Benzo et al. [16], for instance, employed a GA to optimize sandwich panels in a civil engineering application with respect to cost, mass, and environmental impact. However, their study is constrained by a predefined design, a small number of materials and the life cycle differs significantly from applications in aircraft cabins. In terms of general material selection, Zhou et al. [17] developed a multi-objective approach integrating Artificial Neural Networks (ANN) and GAs to account for mechanical properties, and economic and environmental suitability. This approach, however, is limited to applications like drinking bottles, where design complexity is minimal. Similarly, Sohi et al. [18] focused on material selection considering cost and sustainability across the entire product lifecycle, specifically evaluating applications in the automotive industry. Despite offering a comprehensive lifecycle perspective, they did not incorporate detailed finite element (FE) analysis into the design process, leaving a gap in precise design integration. In the domain of aerospace applications, works by Al-Fatlawi et al. [19] and Seyyedrahmani et al. [20] emphasize differing facets of sandwich structure optimization. Al-Fatlawi et al. [19] targeted mechanical parameters exclusively for aircraft containers, omitting cost considerations, while Seyyedrahmani et al. [20] crafted a design methodology for laminated panels using analytical formulas unsuitable for large cabin components. Homsnit et al. [21] research on electric quadricycles addressed the optimization of constituent thicknesses and mechanical properties but does not incorporate material selection or sustainability aspects. Xu et al. [22], in optimizing automotive sandwich panels for minimal mass and maximal sound insulation, also fell short of expanding beyond two objectives and relied on analytical rather than comprehensive design methods. Several studies have begun integrating broader objectives. Salem and Donaldson [23] explored weight and cost optimization, whereas Sahib and Kovács [24] combined GA and ANN to optimize high-speed train floor panels, mainly using FE calculations for validation rather than as drivers of design innovation. Tadamelle et al. [25] faced challenges in scalability and real-world application by focusing primarily on simple bending tests with Multiple-Criteria Decision Making (MCDM) and Topsis methodologies in the context of wind turbines. The potential of bio-based materials in reducing environmental impacts is explored by Martinez et al. [26], who discussed their use in both skins and cores of sandwich laminates. The focus, however, remained on mechanical performance improvements, particularly in aircraft cabin components. Calado et al. [27] presented a notable integration of FE analysis with LCA and LCC to optimize aircraft structure parts. This approach ensures both structural efficiency and sustainability, although it is constrained by only considering variations of a single material and neglecting core materials and geometric design parameters. Despite significant advancements, challenges remain in the multi-objective optimization of sandwich structures, particularly when balancing mechanical with ecological and economic performance metrics. In aircraft design, precise calculations are crucial, and considering a range of material options enhances the selection of sustainable design alternatives. This underscores the need for further investigation into addressing the complicated requirements of modern sandwich structures in aviation. The objective of this study was to develop a procedure for the multi-objective optimization that integrates precise design optimization with a sustainability assessment. This procedure is intended to assist product developers in selecting designs that meet mechanical, environmental, and economic goals, contributing to more sustainable and efficient practices in the industry.

The structure of this paper is as follows: Following the introduction, Section 2 outlines the procedure for multi-objective sustainability and design optimization as well as the used software. In Section 3 this procedure is applied to a case study involving a partition-like sandwich structure as an example for an aircraft cabin component. Section 4 offers a discussion of the results, addressing the limitations of the study and identifying potential areas for future research. Finally, Section 5 provides a summary and outlook.

2. Materials and methods

The developed procedure is illustrated in Fig. 1, along with the software employed for evaluating this procedure using a representative sandwich structure. The procedure commences in the first step with a problem analysis and the formulation of objectives. By the conclusion of this initial step, the design variables and objectives are clearly defined. Subsequently, in the second step raw data corresponding to the potential materials and considered processes is gathered. For data storage, Microsoft Excel and Altair HyperWorks are utilized. The implementation of the underlying performance metrics calculation in the third step is a central aspect of the procedure. To incorporate mechanical design considerations, the procedure distinguishes between mechanical performance metrics, determined through FE analysis, and other performance metrics, calculated using rule-based scripts, such as sustainability or cost-related indicators. These analysis and calculations are implemented using Altair HyperWorks with the solver OptiStruct and Python scripting. The fourth step involves the multi-objective optimization, for which the software Altair HyperStudy is used. The resulting Pareto front provides a set of equivalent yet diverse design alternatives. In the fifth and final step, one design alternative is selected as a compromise solution, taking various perspectives into account.

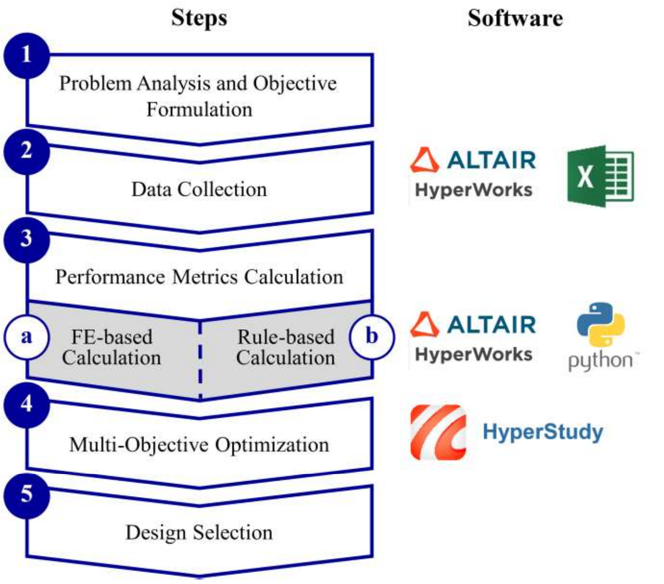

Fig. 1. Procedure for the multi-objective optimization of composite sandwich structures and used software.

3. Results

This section illustrates the procedure using an example of an aircraft partition-like sandwich structure shown in Fig. 2. The aim is to demonstrate the potential for optimizing this sandwich structure with regard to various, particularly sustainable, performance metrics. The first step of the procedure involves the *Problem Analysis and Objective Formulation*. The lightweight structure to be designed is a partition-like sandwich structure, constrained at so-called lower and upper attachments. In the considered load case, the structure is subjected to loads applied orthogonally to the sandwich panel at several load introduction points. The design variables for optimization include the core height, face sheet thickness, and material selection for both the core and the face sheets, while the initial design incorporates a 25 mm Nomex® honeycomb core and a GFRP face sheet with a thickness of 0.25 mm. The objective criteria encompass deflection as a measure of mechanical performance, production costs as an economic metric, and weight along with greenhouse gas (GHG) potential during the production phase as ecological metrics. The GHG potential in the production phase was introduced to highlight an additional sustainability trade-off in the optimization process and because sufficient data in the literature was available. The GHG potential over the entire lifecycle in the aviation industry correlates with the weight, which is why it was not considered. The extension to other performance metrics is possible and valuable if the necessary data is available and if the considered performance metrics can be influenced in the current design stage.

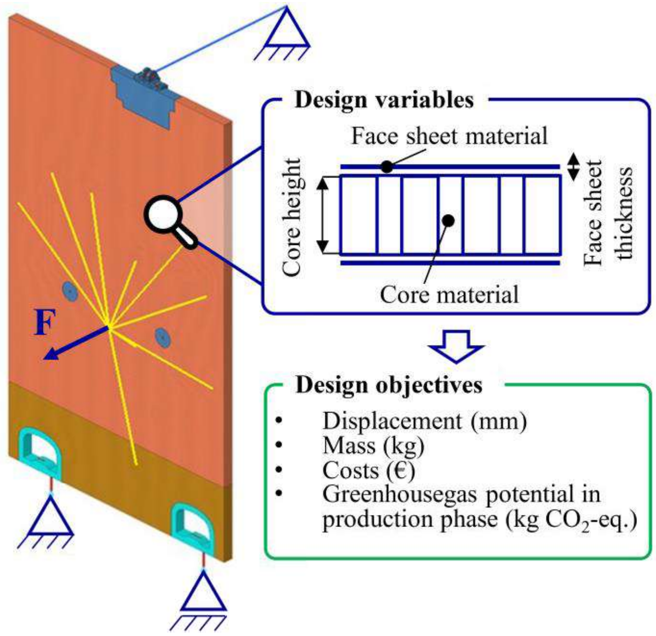

Fig. 2. Sandwich structure with design variables and objectives.

In the second step, which involves the *Data Collection* for raw materials and processes, data essential for further analysis and the calculation of performance metrics is collected and organized into tables or databases. In addition to conventional sandwich materials like glass or carbon fibres, biobased composite materials such as flax or hemp have been included in the optimization process. For the FE modelling mechanical properties like direction-dependent elastic and shear moduli or strengths have been considered. Material density is another critical parameter for simulation and weight calculation. Additionally, the CO_2 equivalents produced during the production phase and material costs were stored. The values in this contribution were sourced from literature, data sheets and homepages. In cases where relevant material data is unavailable, it can be generated through suitable modelling techniques, such as LCA. The data is stored in databases, with an Excel file serving as a medium for access via a Python script for rule-based performance metrics calculation. An input file containing required material parameters was utilized for the FE simulation in Hypermesh.

In the third step, the *Performance Metrics Calculation* is implemented. This calculation is divided into mechanical and rule-based performance metric evaluations. For the mechanical KPI determination, a FE Analysis is conducted. An appropriate FE model is developed, modelling the sandwich structure as a layered composite shell. To handle the numerous simulations required for optimization, the model is parameterized. Variables such as core height and face sheet thickness are implemented, which are later transferred from the optimization environment to the simulation. Materials are assigned via a material ID, which loads the corresponding material model with its inherent properties. The FE model is structured in such a way that deflection results are fed back into the optimization environment for further analysis. Simultaneously, a rule-based performance metric calculation is executed. Material and geometric design parameters serve as inputs to determine the volume of the raw materials considered, forming the basis for subsequent calculations. Using data from the database, economic and ecological performance metrics are derived. Additional rules and scenarios can be incorporated to consider specific manufacturing processes as well. Although the parametrization of the FE model was swift, researching the material values and processes necessary for implementing performance metric calculations took significantly longer.

In the fourth step, the *Multi-Objective Optimization* is conducted. The optimization process is illustrated in Fig. 3. Initially, the boundaries for the design variables are defined. Subsequently, optimization is carried out using HyperStudy's built-in Multi-Objective Genetic Algorithm (MOGA) [28]. A first population is generated, and for each individual in the population, FE simulations and rule-based performance metrics calculations are executed. The calculated KPIs are then fed back into HyperStudy to evaluate the fitness of each design, aiming to maximize an objective function. The design variables are then subjected to mutations, and the process is repeated iteratively until a termination condition is met. For the example, 900 simulations were conducted, each lasting approx. one minute, resulting in a total simulation time of 15 hours. Fig. 4 gives an overview of the design space after the multi-objective optimization. Here the attributes of the design variables and the resulting design objectives are shown. Two exemplary configurations are highlighted. Similar properties could be achieved for both of the design alternatives with different materials and geometrical design values, while the red configuration is more expansive than the orange design alternative. The result of the multi-objective optimization is exemplified in Fig. 5. Although only four design objectives were considered in this example, it is evident that visualizing the Pareto front in a 4D plot is challenging, especially as the number of design objectives increases. Points on the Pareto front in general represent the best available solutions - each optimal in its own right but differing from the others.

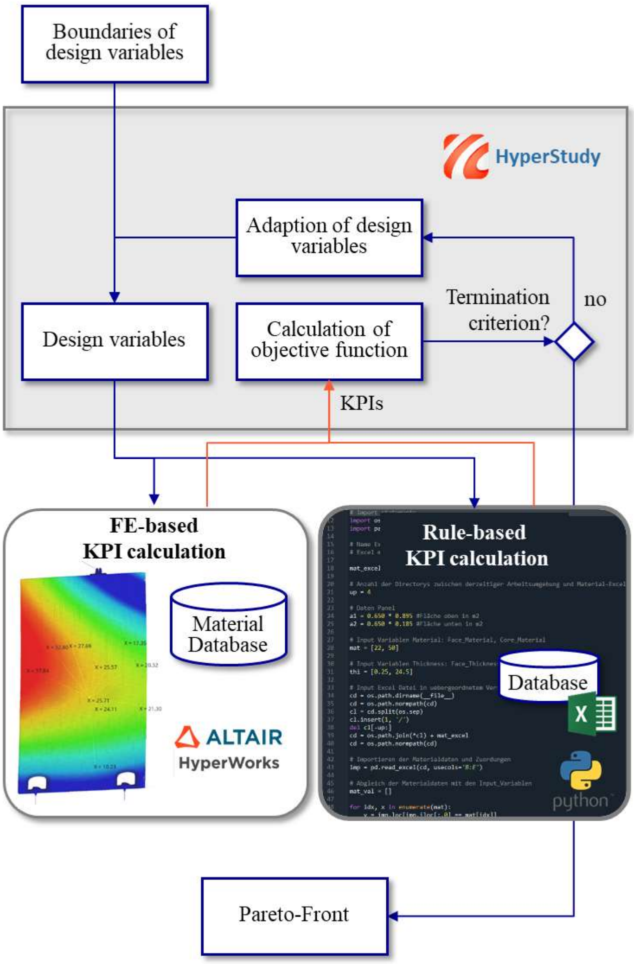

Fig. 3. General procedure for the multi-objective design optimization.

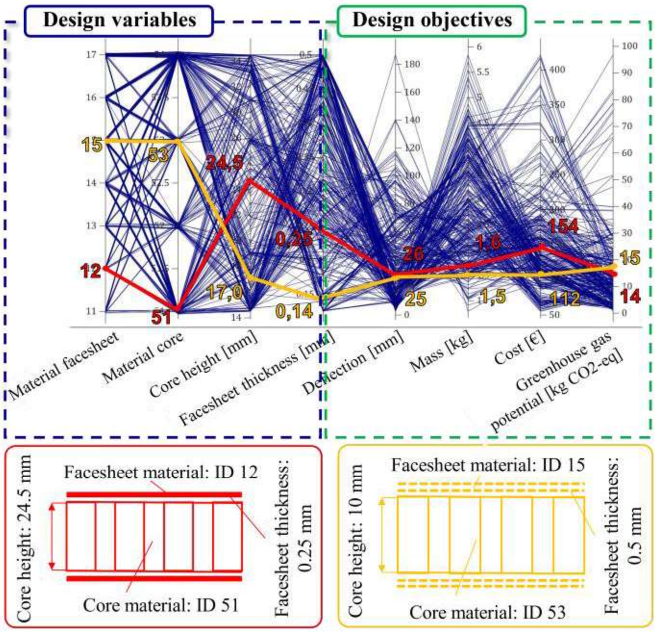

Fig. 4. Design space exploration in HyperStudy with different design variables as input and design objectives as outputs.

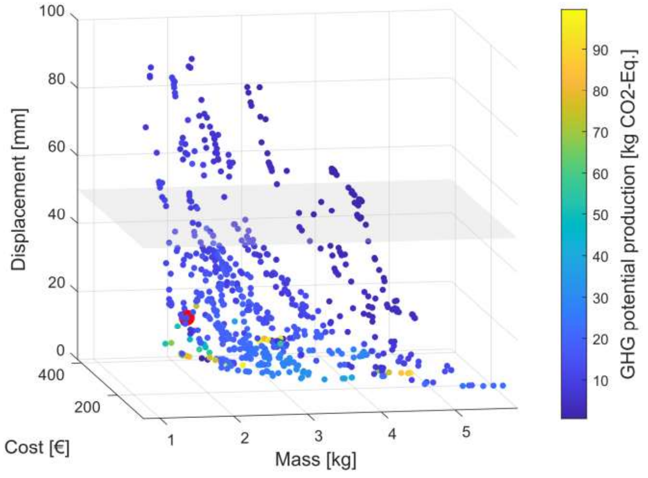

Fig. 5. Design solutions after the Multi-Objective Optimization.

In the final, fifth step, the *Design Selection* takes places. Therefore, a displacement constraint is defined, enforcing a maximum displacement of 50 mm as a non-negotiable condition. Within the reduced solution space, where solutions with a displacement above 50 mm are filtered out, projecting the remaining solutions onto the cost and mass plane results in Fig. 6. A Pareto front can be drawn to identify equivalent alternative solutions, considering that the GHG potentials during production are comparable for all alternatives. The solution marked with a green dot was chosen, as its lower weight enables additional GHG reductions during the use phase. The chosen design solution also incorporates a Nomex® honeycomb core, but with a reduced core height, and uses a different type of GFRP face sheets. This design change, as illustrated in the figure, minimizes over-dimensioning and results in reduced costs (approx. 39%), mass (approx. 25%), and GHG during the production phase (approx. 25%).

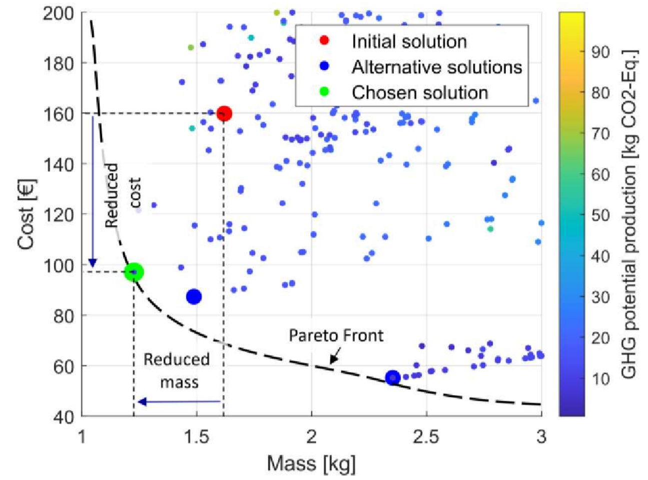

Fig. 6. Pareto front when considering a maximal displacement of 50 mm.

4. Discussion

The presented procedure offers an effective approach for optimizing sandwich structures with respect to multiple design objectives. Notably, the automated and simultaneous calculation of mechanical performance metrics via FE analysis alongside rule-based economic and ecological performance metrics, constitutes an innovative aspect. However, when evaluating the procedure within the context of the case study, simplifications were made, and challenges emerged that hinder efficient application. These challenges can be categorized into three main areas: selection of suitable sustainability criteria and indicators, availability and quality of data for performance metric determination and strategies and timing for MCDM.

Selecting *appropriate criteria and indicators for assessing the sustainability* is a key challenge in multi-objective evaluations of lightweight structures. The primary goal is to enable comprehensive evaluation by addressing numerous SDGs using quantifiable indicators for comparability. A major challenge is the limited data availability in early development phases when the potential to influence product characteristics is greatest. As development progresses, more data become available, but the ability to influence sustainability decreases. This highlights the need to focus on sustainability criteria that can be influenced during specific development phases. Firstly, an overview of all relevant sustainability criteria should be established, followed by identifying those applicable to lightweight design. The aim should be to define a suitable number of criteria for optimization while maintaining essential mechanical requirements as non-negotiable constraints.

Regarding *data availability*, it was found that some data was insufficient. While most data could be sourced from data sheets or literature, the quality varied, which could impact optimization results. When data is unavailable, it can be manually generated, though this requires significant effort. Tools such as LCA or LCC can assist in data generation. This could also help capturing process-dependent parameters and acquiring relevant data. To better integrate processes, utilizing system modelling approaches is also feasible. By incorporating a parallel model-based process simulation, process-dependent performance metrics can be included in the optimization, potentially enhancing the optimization results.

In context of *design selection*, the weighting and comparability of performance metrics are pivotal. In the proposed procedure decision-making follows optimization offering flexibility in adjusting mechanical requirements or criteria weights. These adjustments can be driven by strategic corporate goals or regulatory changes that require reassessment of sustainability metrics or specific indicators. Due to post-optimization weighting, the solution space often remains large. Defining criteria weights and mechanical thresholds in advance can streamline the optimization process by providing a more precisely defined objective function. This would present advantages, which should be evaluated for each application.

5. Conclusion & outlook

In the development of lightweight products, numerous design objectives can be adversely affected by design decisions. For example, while fiber-reinforced lightweight materials can produce lighter products, they often entail high costs, pose health risks, and present recycling challenges. Sandwich structures, in particular, are significantly affected by trade-offs due to their expansive design space. To navigate such trade-offs, this paper introduces a five-step procedure for the multi-objective optimization of sandwich structures, leveraging genetic optimization algorithms. The special feature of the presented procedure lies in the concurrent calculation and optimization of mechanical performance metrics, derived from FE simulations, alongside rule-based ecological and economic performance metrics. This procedure was successfully applied in a case study involving a partition-like sandwich structure, optimizing defined design objectives.

By applying this procedure, three key areas have been identified where future research is required:

- Selection of criteria and indicators influenced by lightweight design for measuring sustainability,
- Data availability and integrated process modelling regarding sustainability performance metrics,
- Methods and timing of multi-criteria decision-making and design selection when addressing trade-offs related to sustainability.

Scientific advancements in these areas will enhance the efficiency of the procedure presented in this work. Ultimately, the procedure can facilitate the early integration of sustainability and their performance metrics into product-specific sandwich design and material selection.

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).

References

[1] Ashby MF. Multi-objective optimization in material design and selection. Acta Mater. 2000;48(1):359-369. doi:10.1016/S1359-6454(99)00304-3

[2] Vos RO. Defining sustainability: a conceptual orientation. J Chem Technol Biotechnol. 2007;82(4):334-339. doi:10.1002/jctb.1675

[3] United Nations, Department of Economic and Social Affairs – Sustainable Development. Accessed November 8, 2022. Available from: https://sdgs.un.org/goals

[4] Finkbeiner M, Schau EM, Lehmann A, Traverso M. Towards life cycle sustainability assessment. Sustainability. 2010;2(10):3309-3322. doi:10.3390/su2103309

[5] ISO 14040: Environmental management—life cycle assessment—principles and framework. Geneva: ISO; 2006.

[6] ISO 14044: Environmental management—life cycle assessment—requirements and guidelines. Geneva: ISO; 2006.

[7] Kaufman RJ. Life cycle costing: a decision-making tool for capital equipment acquisition. Cost Manag. 1970;March-April:21-28.

[8] Aerospace, Security and Defence Industries Association of Europe. 2023 Facts & Figures. Accessed November 12, 2024. Available from: https://www.asd-europe.org/news-media/facts-figures/

[9] 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. Luxembourg: Publications Office; 2011. Available from: https://data.europa.eu/doi/10.2777/50266

[10] Bachmann J, Hidalgo C, Bricout S, Saul. Environmental analysis of innovative sustainable composites with potential use in aviation sector—a life cycle assessment review. Sci China Tech Sci. 2017;60:1301-1317. doi:10.1007/s11431-016-9094-y

[11] Gomez-Campos A, Vialle C, Rouilly A, Hamelin L, Rogeon A, Hardy D, Sablayrolles C. Natural fibre polymer composites – a game changer for the aviation sector? J Clean Prod. 2021;286:124986. doi:10.1016/j.jclepro.2020.124986 [Add to Citavi project by DOI] .

[12] Vidal R, Moliner E, Martin PP, 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. J Ind Ecol. 2018;22(1):132-144. doi:10.1111/jiec.12544

[13] Krause D, Schwenke J, Gumpinger T, Plaumann B. Leichtbau. In: Rieg F, Steinhilper R, editors. Handbuch Konstruktion. 2nd ed. München: Carl Hanser Verlag; 2018. p. 487-507.

[14] BDLI – German Aerospace Industries Association. The role of cabin and cargo for sustainable aviation. Accessed November 11, 2024. Available from: https://www.bdli.de/meldungen/eco-efficient-flying-cabin-and-cargo-major-pillar-sustainable-aviation

[15] Zenkert D. An introduction to sandwich construction. London: Chameleon; 1995.

[16] Benzo PG, Sena-Cruz J, Pereira JM. Multi-objective design optimization of sandwich panel. In: Ilki A, Ispir M, Inci P, editors. 10th International Conference on FRP Composites in Civil Engineering. CICE 2021. Lecture Notes in Civil Engineering. Vol. 198. Cham: Springer; 2022. doi:10.1007/978-3-030-88166-5_203

[17] Zhou CC, Yin GF, Hu XB. Multi-objective optimization of material selection for sustainable products: artificial neural networks and genetic algorithm approach. Mater Des. 2009;30(4):1209-1215. doi:10.1016/j.matdes.2008.06.006

[18] Hashemi Sohi FS, Mansour S, Dehghanian A. Multi-objective optimization for selecting sustainable materials with simultaneous consideration of several components in a product. Int J Sustain Eng. 2022;15(1):107-121. doi:10.1080/19397038.2022.2080888

[19] Al-Fatlawi A, Jármai K, Kovács G. Optimal design of a fiber-reinforced plastic composite sandwich structure for the base plate of aircraft pallets in order to reduce weight. Polymers (Basel). 2021;13(5):834. doi:10.3390/polym13050834

[20] Seyyedrahmani F, Shahabad PK, Serhat G, Bediz B, Basdogan I. Multi-objective optimization of composite sandwich panels using lamination parameters and spectral Chebyshev method. Compos Struct. 2022;289:115417. doi:10.1016/j.compstruct.2022.115417

[21] Homsnit T, Kongwat S, Ruangjirakit K, Noykanna P, Jongpradist P, Thuengsuk T. Optimizing stiffness and lightweight design of composite monocoque sandwich structure for electric heavy quadricycle. Lat Am J Solids Struct. 2023;20(3). Published April 5, 2023.

[22] Xu X, Jiang Y, Lee HP. Multi-objective optimal design of sandwich panels using a genetic algorithm. Eng Optim. 2017;49(10):1665-1684. doi:10.1080/0305215X.2016.1265304

[23] Salem AI, Donaldson SL. Weight and cost multi-objective optimization of hybrid composite sandwich structures. Int J Comput Methods Exp Meas. 2017;5(2):200-210. doi:10.2495/CMEM-V5-N2-200-210

[24] Sahib MM, Kovács G. Elaboration of a multi-objective optimization method for high-speed train floors using composite sandwich structures. Appl Sci. 2023;13(6):3876. doi:10.3390/app13063876

[25] Tadamalle AP, Katikar RS, Gandhare BS, et al. Selection, optimization and analysis of core and face material for wind turbine composite blade. Int J Interact Des Manuf. 2024. doi:10.1007/s12008-024-02024-5

[26] Martínez X, Pons-Prats J, Turon F, Coma M, Barbu LG, Bugeda G. Multi-objective multi-scale optimization of composite structures, application to an aircraft overhead locker made with bio-composites. Mathematics. 2023;11(1):165. doi:10.3390/math11010165

[27] Calado EA, Leite M, Silva A. Selecting composite materials considering cost and environmental impact in the early phases of aircraft structure design. J Clean Prod. 2018;186:113-122. doi:10.1016/j.jclepro.2018.02.048

[28] Altair HyperWorks. Multi-Objective Genetic Algorithm (MOGA). Accessed November 12, 2024. Available from: https://2017.help.altair.com/2017/hst/hst.htm?moga.htm