Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 00 (2019) 000–000

www.elsevier.com/locate/procedia

31st CIRP Design Conference 2021 (CIRP Design 2021)

Simulation-based design: A case study in combining optimization methodologies for angle-ply composite laminates

Evangelos Tyflopoulos[a]*, Tarjei Aure Hofset[a], Anna Olsen[a], Martin Steinert[a]

[a]*Department of Mechanical and Industrial Engineering, NTNU, Richard Birkelandsvei 2B, Trondheim 7034, Norway*

* Corresponding author. Tel.: +4747730242. *E-mail address:* evangelos.tyflopoulos@ntnu.no

---

Abstract

Over the last decades, the intense need for more robust and lightweight structures, together with the dramatic improvement of computational power, had, as a result, the introduction of simulations in the traditional product development. As a simulation, it is considered any computer process that imitates a real system by generating similar responses over time. Simulations allow the designers to create virtual prototypes that can speed up the design phase and, thus, the product development time in total. This design paradigm shift is called simulation-based design (SBD) and includes several simulations and optimization techniques. The most notable of these techniques are; computer-aided design (CAD), finite element analysis (FEA), topology optimization (TO), and parametric optimization (PO). A combined SBD methodology, including these techniques, is presented here. This methodology is a two-stage optimization process. During the first stage, traditional compliance TO using the SIMP approach was conducted, while at the second, a PO with an evolutionary algorithm was applied. The presented methodology is focused on the optimization of composite laminates. In particular, an angle-ply laminated beam made by carbon fiber reinforced polymer (FRP) was used as a case study and optimized both for its topology and fibers' direction. The results of this research are presented and tested using a commercial example. The suggested methodology resulted in a lighter and more robust design solution. These design solutions can be constructed either by conventional manufacturing processes (CMP) or by additive manufacturing (AM). Designers looking for interesting and lightweight composited structures can exploit the results found in this paper. The implemented process can easily be modified in order to cover any possible optimization of FRP products.

© 2021 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 31st CIRP Design Conference 2021

Keywords: composite laminates; topology optimization; simulation-based design

---

1. Topology and Parametric Optimization as Simulation-based design tools

Topology Optimization (TO) and Parametric Optimization (PO) are two popular optimization techniques that have been broadly used either independently or in combinations in structural optimization [1]. These optimization techniques originate from the previous century. Box and Wilson [2] applied the first form of PO trying to leverage their experimental data, while Michell and later Bendsøe [3], with the homogenization method, are considered as the pioneers of the TO. Readers interested in the theoretical background of these techniques should be referred to the aforementioned research papers.

The current state of the art of TO is about three main issues; the reduction of the simulation time, the mitigation of the results' sensitivity, as well as the reduction of the designer's inputs in the optimization process. In other words, TO is a difficult and time-demanding procedure, which is also sensitive to designer choices. Thus, there is a need for a more

2212-8271 © 2021 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0)
Peer-review under responsibility of the scientific committee of the 31st CIRP Design Conference 2021

automatic and effective optimization procedure [4]. Many research papers are focused on either the development of new optimization algorithms or the improvement of the existing ones with respect to their efficiency, especially for large-scale and multidisciplinary optimization. On the other hand, the development of other approaches, such as the generative design, try to automate the optimization procedure while they increase the design flexibility and, thus, the designers' choices. The automation of the optimization procedure is also the primary goal of this paper.

Both PO and TO can be considered as two iterative design techniques that can be used in the design phase of product development. These techniques eliminate the backs and forwards between detailed design and validation by placing the latter in the front place of this process. This design approach is mainly known under the term Simulation-based design (SBD). The SBD is the design procedure where a series of simulations is considered as design evaluation and verification [5]. It applies different computer tools and algorithms in order to optimize the design of a structure and always with respect to the given parameters. The simulation-driven design process here replaces the traditional one resulting in better and more optimal designs. The prototypes in simulation-based product development are the derived numerical models. These models can be used to tackle complex optimization problems and, thus, refine the final designs of the products.

As it is depicted in Figure 1, the SBD that also integrates the optimization phase is a simultaneous implementation of the following three phases; the design concept phase, the simulation phase, and the optimization phase. At the design phase, the designer develops all the possible design ideas that fit the given boundary conditions. Afterward, these design concepts will be checked for their validity using computer-aided engineering (CAE), such as finite element analysis (FEA). In the case that the product should be optimized with respect to some given criteria (thickness, mass, etc.), an optimization technique such as PO and TO can be conducted, either in sequence or in parallel with the other two phases. The most important advantage of the SBD is that all these phases can be applied as a loop exploiting the computational power [6]. Thus, the designer's inputs can be limited to an initial design concept. It is the software and not the designer that will suggest alternative design concepts based on the initial design and the given boundary conditions. However, the initial design concept, the boundary conditions, and the choice of the final design are still the designer's responsibility.

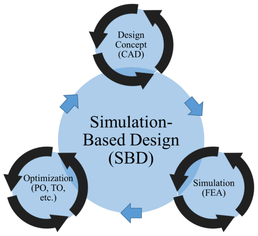

Figure 1. A schematic illustration of a Simulation-Based Design (SBD).

A semi-automatic optimization methodology is presented in this paper. The conducted methodology is a simulation-based technique that contains an automatic loop of PO. In this way, the designer's inputs are reduced, and thus, the design time is decreased. A case study of an angle-ply laminate beam made by carbon fiber reinforced polymer (FRP) was used to apply this methodology. The beam was optimized for both its topology and fibers' direction (layup). The optimized design was further compared to a commercial beam found in the literature that is used in aeronautics. The authors' intention was to compare the beam to a similar one with an optimized layup but not an optimized topology as a prerequisite. Thus, they could highlight the need for a TO of the part before the PO of the plies' angle. Designers looking for interesting and lightweight composite structures, such as carbon fiber reinforced polymers, can exploit the insights from this paper. These structures can be used in the construction of long flat products such as alpine skis and snowboards.

According to Wang, Yu [7], composites are multiphase materials that combine the properties of their components. Hence, their mechanical properties can outperform the properties of their components alone. One commercial category of composite materials is the fiber-reinforced polymers (FRP) that consist of polymer resins and high strength fibers like glass, carbon, and aramid (see Figure 2a). A stack of multiple FRP layers, also called plies, are bonded together using adhesives, creates the laminates (see Figure 2b). The composite laminates, depending upon the stacking sequence nature, can be classified into seven categories; symmetric, cross-ply, angle-ply, anti-symmetric, balanced, orthotropic, and quasi-isotropic laminates [8]. The category that is relevant for this paper is the angle-ply laminates. This type of laminates consists of a random number of plies of the same thickness and material while they have various fiber directions (ply angle) between -90 and +90 degrees. Plies with different angles are stacked in a laminate when there is a need for load-carrying capacity optimization in different directions [9]. Due to their lightweight structure and robustness, laminates widely find application in automobile, aerospace, sport utilities, etc. However, they are characterized by their anisotropic properties that make their design and construction challenging. Furthermore, there is a clear gap in in-depth knowledge about the mechanical properties of FRP in general.

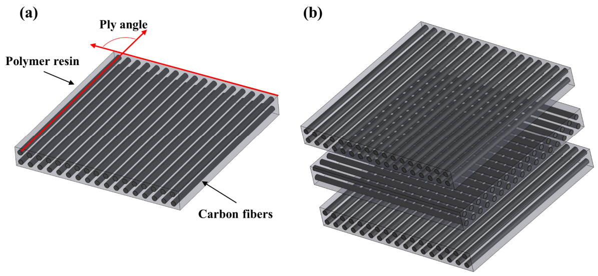

Figure 2. a) A ply (layer) and b) A composite laminate consisting of stacking plies.

The basic outline of the remainder of the paper is as follows; in Section 2, the implemented methodology, as well as the theoretical background, are described in detail. The results are presented and discussed in Section 3, and finally, the conclusions and the future research based on the findings are presented in Sections 4 and 5, respectively.

2. Method

An automatic loop for the TO and the optimal composite composition of an angle-ply laminate beam is presented in this paper. The conduced approach can be described as a two-stage process where the first stage generates the optimal part topology, and the second creates an optimal layup configuration. The authors' intention was to eliminate the designer's inputs and let the chosen software choose the optimal design solution. The applied SBD methodology is presented by a flowchart depicted in Figure 3. The two-stage procedure is divided into five main steps: 1) Pre-processing, 2) TO, 3) Post-processing, 4) PO, and 5) Validation.

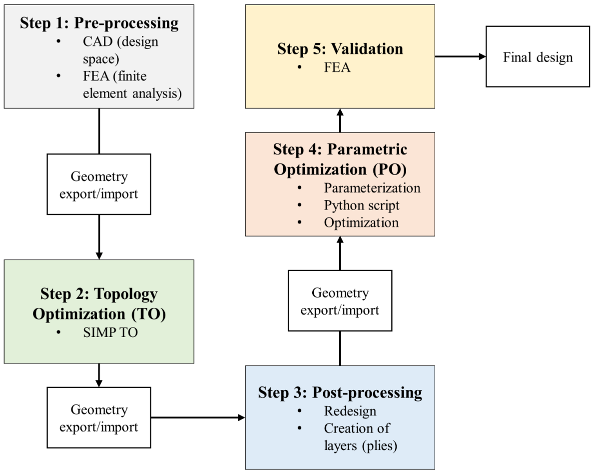

Figure 3. The applied methodology in this research.

The Pre-processing step consists of two main activities; the CAD and the FEA. At this step, the designer decides the used design space and all the inputs for the FEA simulations. According to Tyflopoulos and Steinert [10], the designer's inputs in the front-end phase of an SBD-method can be categorized into four clusters; design constraints, supports and connections, load cases, and geometric restrictions due to manufacturing constraints. In these inputs, the TO and PO options can be added too. As has already been mentioned, a case study of a 200x6x200 mm (LxWxH) thin beam was used in this paper to present the implemented method and support the theory. The initial 3D-model was designed in the SolidWorks CAD software, including all the relevant geometrical features that both are required for the final component and can influence the optimization results. Once the design space was defined, the model was transferred to Abaqus FEA software, where two load cases were applied, resulting in both torsional and bending deformation of the part. Then, the model was discretized into 5 mm hexahedral finite elements, leading to 16000 elements in total. An arbitrary elastic isotropic material with E=50 GPa and v=0.3 was assigned to the model. The elastic modulus for the isotropic design space was significantly less than the equivalent anisotropic lamina values, as will be presented at the PO step. The initial design of the part, as well as the applied loads and boundary conditions, are shown in Figure 4.

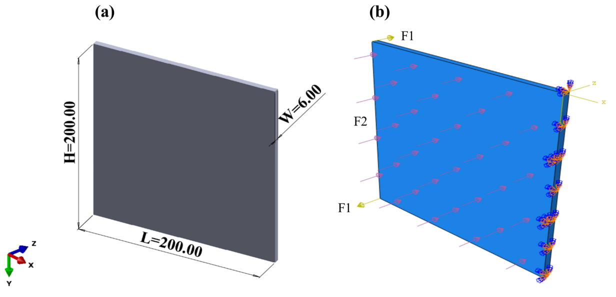

Figure 4. a) The initial design of the used model, and b) The FEA model: fixed on the right side, F1= 10N and F2=5N.

At the next step, the TO was conducted using the Tosca structure optimization software with the same boundary conditions and loading scenarios. The Solid Isotropic Material with Penalization method (SIMP) was used with strain energy and volume as objective function and design response, respectively. The sum of the elements' strain energy is equal to the compliance, which is the reciprocal of the stiffness. Thus, the designers using this approach try to reduce the material of the structure while they keep its robustness. The applied algorithm minimized the total strain energy of the structure using as a constraint a 50% volume reduction. The SIMP method was initially proposed by Bendsøe and Kikuchi [11]. This method utilizes the density distribution within a discrete design domain ρ, where a binary value is assigned:

$$\rho_e = 1, \text{ where material is required} \tag{1}$$

$$\rho_e = 0, \text{ where material is removed (void)} \tag{2}$$

The transformation from discrete to continuous values ($0 \leq \rho \leq 1$) allows the creation of intermediate densities. In this case, the Young modulus of each element is given by the following power law:

$$E(\rho_e) = \rho_e^p E_0 \tag{3}$$

Where p is the penalization factor that diminishes the total stiffness due to the intermediate densities. According to Zhou, Pagaldipti [12], p must be between 2-4, and usually, its value is 3. The reduction of the material elastic modulus leads, in its turn, to a stiffness reduction. The global stiffness of a structure is given by the formula:

$$K_{SIMP(\rho)} = \sum_{e=1}^{N} [\rho_{min} + (1 - \rho_{min})\rho_e^p] K_e \tag{4}$$

where:

ρ_{min}: the minimum allowable relative density value for void elements that are greater than zero

K_e: the element stiffness matrix

p: the penalty factor

N: the number of elements in the design domain

Thus, in the traditional compliance TO approach, which is also used here, the objective function is:

$$\min C(\{\rho\}) = \sum_{e=1}^{N} (\rho_e)^p [u_e]^T [K_e][u_e] \tag{5}$$

where:

$[u_e]$: the nodal displacement vector of element e

$[K_e]$: the stiffness of element e

$\{\rho\}$: vector that contains the elements' relative densities

In addition, during each optimization iteration, the target volume constraint (50%), the global force-stiffness equilibrium, as well as possible functional constraints must be satisfied. Here, a forging constraint was added to support the manufacturability of the optimized design. Forging is a special case of casting. In this case, the forging die needs to be pulled only in one direction. Hence, this constraint adds geometric restrictions to the optimized designs by creating a virtual central plane internally on the back plane of the model. In this way, the pulling takes place in only one direction [13]. Furthermore, the regions with the applied loads were excluded from the design space of the TO. Finally, 50 design cycles were chosen as a limit for the implementation of the TO.

The optimized design was exported as a STEP file and imported in SolidWorks for the Post-processing. Here, a redesign of the part was conducted with regard to manufacturability. Thus, organic shapes and complex geometries of the structure were either removed or redesigned. At that point, the derived model was sliced into four cross-sections (sets) for the sake of redesign simplicity.

The updated design was introduced again into Abaqus for the PO. The used thickness of the plies was equal to 0.3 mm, and thus, 20 plies were created in total. Each cross-section had a corresponding ply in a way that when the plies were stacked on top of each other, the resulting composite part would match the geometry taken from the TO. A new unidirectional pre-impregnated carbon fiber material, Hexcel 6376, was added for the laminas. This material is an orthotropic high-performance matrix formulated composite. The required data in order to calculate the orthotropic elasticity of the structure in-plane stress are the principal young moduli E_1 and E_2, the poison's ratio in the principal direction Nu_{12}, as well as the shear moduli in the principal directions G_{12}, G_{13}, G_{23} [14]. The shear moduli are needed to define the transverse shear behavior in shells. An overview of all these data is summarized in Table 1.

Table 1. Material properties for the Hexcel 6376

Symbol	Value [GPa]	Description
E_1	164	Young's modulus in the fiber direction
E_2	9	Young's modulus in the matrix direction
Nu_{12}	0.31	Poisons ratio
G_{12}	6.5	in-plane shear modulus
G_{13}	6.5	in-plane shear modulus
G_{23}	6.5	in-plane shear modulus

At that moment, an evolution-based parametric optimization model was developed in the Isight software in order to optimize the FRP-material layup. The used evolutionary optimization algorithm is based on the works of Rechenberg [15] and Schwefel [16]. The evolution strategy developed to solve continuous parameter optimization problems with the following form:

$$f: M \subseteq R^n \rightarrow R, \text{ with } M \neq 0 \tag{6}$$

Where f is the objective function. Kursawe [17] extended (6) in a more general form in order to can solve multiple-criteria problems:

$$f: M \subseteq R^n \rightarrow R^k, k > 1 \tag{7}$$

Thus, the global optimization problem is described as:

$$\forall\, x \,\epsilon\, M: f(x) \geq f(x^*) = f^* \tag{8}$$

where f^* is a global minimum, and x^* is a global minimizer. In addition, for a problem with inequality constraints:

$$g_j: R^n \rightarrow R \tag{9}$$

the feasible region M is characterized by:

$$M = \left\{ x \epsilon R^n \middle| g_j(x) \geq 0 \quad \forall j \in \{1, \ldots, q\} \right\} \tag{10}$$

The algorithm mutates designs by adding a normally distributed random value to each design variable. The standard deviation of the normal distributions is self-adaptive and alters thought the optimization process. The optimization parameter for the conducted PO was the ply angle. The orientation of the angles could be varied from -90 to +90 degrees. As for the TO, the minimization of the total strain energy, and thus the maximizing of the stiffness, was chosen as a goal also here. A Python script applied a given layup configuration to the model in Abaqus before each iteration. The flexibility inside the Python script allows the user to change the parameters and test different layup configurations. The Python script is available for interested readers at the following link: https://github.com/vagelan/A-combined-optimization-methodology-for-optimizing-angle-ply-composite-laminates.git. Isight reads the strain energy values after each iteration and optimizes them by using an evolution strategy.

Finally, for the validation step, a conventional part from the literature was chosen for comparison. The part was adapted from the paper of Bruyneel, Craveur [18]. This is a 200x3.6x200 mm quasi-isotropic laminated beam with similar mass, a uniform thickness, and a conventional plies orientation [0˚/±45˚/90˚] that is mainly used in aeronautics. Furthermore, it consists of 12 plies with the same thickness equal to 0.3 mm. The main difference between the optimized, in this paper, beam and the adapted one is that the first was generated after a two-stage optimization process where its topology and then its layup were optimized while the adapted beam was optimized only for its layup. The validation study was conducted in Abaqus.

As can be observed, there are still many designer's inputs that can delay and affect the optimization procedure and, thus, the final design solutions. However, the development of an automatic loop for layup optimization could decrease the inputs and, thus, the optimization time and the sensitivity of the design solutions.

3. Results

The TO step resulted in a raw faceted geometry that was imported and redesigned in SolidWorks. The TO procedure could be converged after 24 design cycles. The volume of the raw optimized model was reduced by 47.5% compared to the initial design. The redesigned model, after the step of post-processing, had a smoother surface with no stress concentrations and complex geometries. However, the redesign process increased the volume of the model by 8.33%. The initial, optimized, and redesigned models are illustrated in Figure 5.

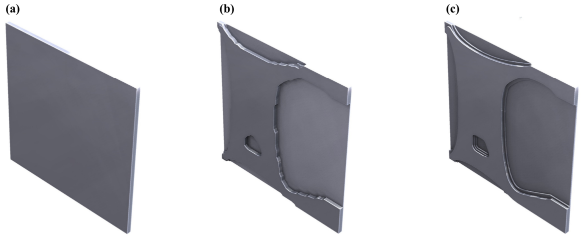

Figure 5. a) The initial design, b) The exported topological optimized design, and c) The design solution after the redesign.

The PO process could be converged after 850 iterations. The composite stacking sequences with their corresponding ply angles for the optimized and the conventional beam are depicted in Figure 6. The ply orientation for the optimized beam varied from -58˚ to +90˚ among the different layers of the four sets, while at the conventional part, the ply-angles alternated among 0˚/±45˚/90˚.

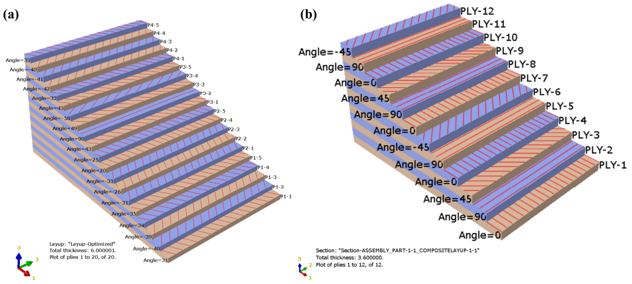

Figure 6. The ply stack plots in Abaqus of a) the optimized beam and b) the convention beam.

The validation step showed that the optimized part was 75.6% stiffer than the conventional part that was used for comparison. In addition, lower maximum Von-Mises stress and deflection were found at the optimized part. The results from the validation study are presented in Table 2. Furthermore, the deflection in the z-direction of the two parts is depicted in Figure 7.

Table 2. The results of the validation study.

Part	Thickness [mm]	Volume [mm^2]	Layup	Str. Energy [J/mm^3]	Deflection [mm]	Stress [MPa]
Optimized	6	1.46E+05	-58 to +90	135	2.6E-01	6.86E00
Conventional	3.6	1.44E+05	0/±45/90	554	1.09E00	1.78E+01

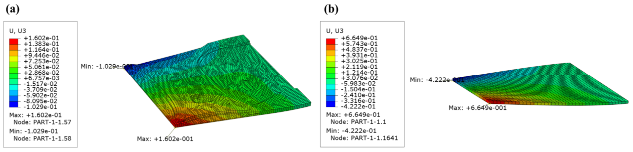

Figure 7. The deflection in the z-direction of the: a) optimized part, and b) the conventional part.

The used case study in this paper was an angle-ply laminated beam. TO was implemented in order to identify the optimized design layout of the structure. The ideal layout could be identified after a small number of design cycles of TO in Abaqus. This, in its turn, was used as a design space for the PO loop. The PO was time demanding; however, it was developed as an automatic procedure that could skip the designer input and result in stronger design solutions. It is clear that the angle-ply laminated beam outperformed the commercial example of a quasi-isotropic laminated beam that was used for comparison reasons. The implementation of the TO before the PO of the plies orientation could contribute to the identification of a stronger design solution making it a prerequisite in the optimization process. The design solution, as well as the implemented SBD methodology, could be used in the industry in the manufacturing of aircrafts or sport utilities. The redesign of the topologically optimized design allows the manufacturing of the laminated beams with both conventional production methods (CPM) and additive manufacturing (AM). The geometry complexity, and the production cost and time could be used as evaluation criteria for the final decision.

4. Conclusions

The purpose of this research was to develop an as much as possible automatic SBD-method for the optimization of angle-ply composite laminates. In particular, a 200x6x200 mm beam of Hexcel 6376 was used as a case study to test the implemented methodology. The findings from this research can be used as a guide in the construction of composites.

The main goal of the authors was to decrease the designer inputs in the optimization loop. A two-stage optimization methodology was developed that encompassed both TO and PO. Generally, it consisted of five sequential steps: 1) Pre-processing, 2) TO, 3) Post-processing, 4) PO, and 5) Validation. The designer's inputs can be mainly found in the pre -and post-processing. The former consists of the aforementioned five parameter clusters; design constraints, supports and connections, load cases, and geometric restrictions due to manufacturing constraints. The latter is about the designer's choices in the redesign of the topologically optimized geometry. The designer should expect a slight discrepancy exporting the faceted design derived from the TO. Thus, there is a need for redesign based on the topologically optimized solution. In addition, the volume of the redesigned model was increased to a small extent. Hence, the design solutions at this point are biased and based on the designer's choices and skills. Another cluster of design inputs could consider the properties and the parameters of the TO and PO, respectively. However, an automated PO loop, at step four, could reduce the designer's inputs and, thus, the simulation time.

The applied TO approach was a traditional compliance optimization using the SIMP method while the PO was executed using an evolution strategy and having as optimization parameter the ply angle. The SIMP method cannot consider the material anisotropy; however, it was used here due to its simplicity. It is possible for the designer to modify the Python script in order to optimize the structure using other parameters such as the plies' thickness and the fibers' material. The volume of the optimized design was reduced by 47.5%. In addition, the validation study showed that the final design solution was 75.6% stiffer than the conventional one.

5. Future research

It is clear that the designer using the presented methodology needs different software expertise. Furthermore, there is still much room for improvement concerning the reduction of his/her inputs, and thus, process automation. However, SBD's benefits of utilizing a tailored process to design complex composite parts are evident. The implemented methodology is characterized by its ease-of-use and applicability and thus can be exploited by designers with no or little experience with composites. Moreover, it is a flexible and scalable process, which could be extended, i.e., to sandwich composites using different materials and load cases. Several TO and PO approaches could be tested. Furthermore, alternative objective functions and additional constraints could be used in both approaches. In addition to that, other TO methods could be applied, such as the method of moving asymptotes (MMA) and the Level-set method. Finally, the construction of real-world parts could help the verification and validation of the implemented process.

References

[1] Tyflopoulos E, Steinert M. Topology and Parametric Optimization-Based Design Processes for Lightweight Structures. Applied Sciences. 2020;10(13):4496.

[2] Box GE, Wilson KB. On the experimental attainment of optimum conditions. Journal of the Royal Statistical Society: Series B (Methodological). 1951;13(1):1-38.

[3] Bendsøe MP. Optimal shape design as a material distribution problem. Structural optimization. 1989;1(4):193-202.

[4] Tyflopoulos E, Flem DT, Steinert M, Olsen A. State of the art of generative design and topology optimization and potential research needs. DS 91: Proceedings of NordDesign 2018, Linköping, Sweden, 14th - 17th August 2018 DESIGN IN THE ERA OF DIGITALIZATION: The Design Society; 2018. p. 15.

[5] Shephard MS, Beall MW, O'Bara RM, Webster BE. Toward simulation-based design. Finite Elements in Analysis and Design. 2004;40(12):1575-98.

[6] Banks J, editor Introduction to simulation. Proceedings of the 31st conference on Winter simulation: Simulation---a bridge to the future-Volume 1; 1999.

[7] Wang G, Yu D, Kelkar AD, Zhang L. Electrospun nanofiber: Emerging reinforcing filler in polymer matrix composite materials. Progress in Polymer Science. 2017;75:73-107.

[8] Staab G. Laminar composites: Butterworth-Heinemann; 2015.

[9] Modak P, Hossain MJ, Ikram I, Ahmed SR, editors. A comparative analysis of elastostatic responses of a cross-ply and angle-ply laminated panel using a single-variable lamination theory. Procedia Engineering; 2014: Elsevier.

[10] Tyflopoulos E, Steinert M. Messing with boundaries-quantifying the potential loss by pre-set parameters in topology optimization. Procedia CIRP. 2019;84:979-85.

[11] Bendsøe MP, Kikuchi N. Generating Optimal Topologies in Structural Design Using a Homogenization Method. Computer Methods in Applied Mechanics and Engineering. 1988;71(2):197-224.

[12] Zhou M, Pagaldipti N, Thomas H, Shyy Y. An integrated approach to topology, sizing, and shape optimization. Structural and Multidisciplinary Optimization. 2004;26(5):308-17.

[13] Dassault Systèmes D. Abaqus analysis user's guide. Technical Report Abaqus 6.14 Documentation, Simulia Corp; 2016.

[14] David Müzel S, Bonhin EP, Guimarães NM, Guidi ES. Application of the Finite Element Method in the Analysis of Composite Materials: A Review. Polymers. 2020;12(4):818.

[15] Rechenberg I. Evolutionsstrategien: Springer; 1978. 83-114 p.

[16] Schwefel H-P. Numerische optimierung von computer-modellen mittels der evolutionsstrategie.(Teil 1, Kap. 1-5): Birkhäuser; 1977.

[17] Kursawe F, editor A variant of evolution strategies for vector optimization. International Conference on Parallel Problem Solving from Nature; 1990: Springer.

[18] Bruyneel M, Craveur G, Beghin C. Optimal design of composite structures with design rules and manufacturing constraints, based on continuous design variables. 2013.