A CONCEPT OF MULTI-CRITERIA OPTIMIZATION OF GLASS-FIBER COMPOSITES FOR MECHANICAL ENGINEERING.

Abstract. *The article provides a theoretical foundation for a multi-objective optimisation framework for glass-fibre-reinforced composites used in mechanical engineering structures. The interrelationships among the material, structural, manufacturing, operational, economic, and environmental parameters governing the performance of composite components are examined. A sequence of optimisation procedures is established, encompassing the specification of structural requirements, selection of design variables, formulation of objectives and constraints, numerical modelling, and identification of a set of Pareto-optimal solutions. The necessity of simultaneously considering strength, stiffness, weight, durability, cost, and manufacturability is substantiated. The use of an aggregate performance measure for ranking compromise solutions according to predefined priorities is justified. Particular attention is given to the effects of material-property variability, manufacturing deviations, and operational loads on the robustness of design solutions. The proposed framework combines multi-objective search methods with finite element modelling, sensitivity analysis, and experimental validation. Its implementation enables an informed selection of the composition and reinforcement architecture of glass-fibre-reinforced composites, taking into account the intended application, manufacturing conditions, and the life cycle of the mechanical engineering structure.*

Keywords: *glass-fibre-reinforced composite, multi-objective optimisation, mechanical engineering structure, Pareto optimality, reinforcement architecture, manufacturability, life cycle.*

Relevance of the Research Problem. The use of glass-fibre-reinforced composite materials in mechanical engineering is driven by their high specific strength, low weight, corrosion resistance, and the possibility of tailoring their properties to specific operating conditions. These materials are employed in structural casings, blades, tanks, pipelines, and thin-walled components.

The performance of a glass-fibre-reinforced composite depends on the types of fibre and matrix, fibre volume fraction, fibre orientation, stacking sequence, laminate thickness, and manufacturing technology. Variations in these parameters simultaneously affect the strength, stiffness, weight, durability, manufacturability, and cost of the resulting component. Improving one performance indicator is often accompanied by the deterioration of another; therefore, single-objective optimisation does not provide a sufficiently well-founded design solution.

Mechanical engineering structures require the simultaneous consideration of mechanical, operational, manufacturing, economic, and environmental requirements. This necessitates the application of multi-objective optimisation, which yields a set of compromise solutions representing different trade-offs among the specified performance objectives.

Therefore, the relevance of this study arises from the need to establish a scientifically grounded framework for the multi-objective optimisation of glass-fibre-reinforced composites for mechanical engineering applications. Its implementation will improve the rationale underlying the selection of material architectures and provide a balanced combination of structural strength, weight, durability, manufacturability, and cost.

Analysis of Recent Research and Publications. Current research on fibre-reinforced composites is focused on the simultaneous consideration of their mechanical, weight and dimensional, manufacturing, and economic characteristics. Z. Hu systematised topology optimisation methods for fibre-reinforced composite structures [1]. Z. Hu, O. Vambol, and S. Sun proposed methods for the simultaneous optimisation of structural topology and fibre orientation and investigated the optimisation of laminated structures subjected to harmonic loading [2; 3]. R. Ghadge, R. Ghorpade, and S. Joshi reviewed the methodological foundations of multidisciplinary design optimisation for composite structures [4].

X. Liu et al. investigated the multi-objective optimisation of manufacturing parameters for glass-fibre-reinforced components [5], whereas Y. Chen et al. systematised intelligent methods for predicting composite properties [6]. The application of neural-network models and genetic algorithms was examined by B. Miller and L. Ziemiański [7; 11]. The optimisation of processing parameters for glass-fibre-reinforced plastics and the reinforcement architectures of hybrid glass-Kevlar composites was addressed by S. Huang, T. Jambhulkar, and R. K. Sahu [8; 9]. L. Rozova et al. proposed a multi-objective approach to the design of composite pressure vessels [10].

Nevertheless, an integrated approach combining the composition of glass-fibre-reinforced composites, their reinforcement architecture, manufacturability, durability, and life-cycle cost remains insufficiently developed, thereby defining the focus of the present study.

Main Results and Discussion. Multi-objective optimisation of glass-fibre-reinforced composites involves the coordinated determination of material composition, reinforcement architecture, and manufacturing parameters in accordance with the functional requirements imposed on a mechanical engineering structure. Unlike single-objective optimisation, which seeks the extremum of an individual performance measure, a multi-objective formulation is intended to identify rational trade-offs among potentially conflicting criteria. This approach is particularly relevant to composite materials because their effective properties are governed concurrently by the characteristics of their constituents, reinforcement architecture, laminate configuration, and the structural response of the finished component.

Conceptually, the optimisation procedure should be formulated as a sequence of interrelated stages: definition of structural requirements;

identification of design variables; formulation of objective functions and constraints; development of computational models; generation of a set of compromise solutions; assessment of their robustness with respect to uncertainty; and selection of a rational design. This sequence establishes a consistent relationship among material properties, reinforcement architecture, manufacturing technology, and the in-service performance of the component.

The principal design variables include the type of glass fibre and polymer matrix, fibre volume fraction, fibre orientation, number and stacking sequence of plies, laminate thickness, geometric parameters of the structure, and processing conditions. Some of these variables are continuous, including ply thickness and fibre volume fraction, whereas others are discrete, such as matrix type, number of plies, and stacking sequence. The simultaneous presence of continuous and discrete variables increases the complexity of the optimisation problem and necessitates the use of hybrid optimisation algorithms [2].

The selection of objective functions must reflect the intended application of the component under consideration. Strength, stiffness, and fatigue life may constitute the governing criteria for highly loaded structural elements. In moving components, weight minimisation becomes an additional priority, whereas tanks and pipelines require leak tightness and resistance to internal pressure and chemically aggressive environments [10]. For serial production, manufacturability, consistency of product properties, and production cost must also be considered. Consequently, no universal set of optimisation criteria can adequately represent all classes of glass-fibre-reinforced composite structures [4].

In general form, the multi-objective optimisation problem may be formulated as the determination of the design-variable vector x that optimises a prescribed set of objective functions:

$$F(x) = [f_1(x), f_2(x), \ldots, f_m(x)] \rightarrow opt \quad (1)$$

where x is the vector of material, reinforcement-architecture, geometric, and manufacturing-process parameters; f_1, f_2,...,fm are the objective functions; and m is the number of optimisation criteria.

For a mechanical engineering structure, the objective functions may include minimisation of weight and cost, maximisation of strength, stiffness, and fatigue life, and minimisation of sensitivity to manufacturing deviations. Because some characteristics are to be maximised whereas others are to be minimised, all criteria must be transformed into a consistent mathematical form and, where necessary, normalised before the optimisation procedure is performed.

The optimisation is conducted subject to a set of constraints defining the feasible design space:

$$g_i(x) \leq 0, j = 1, \ldots, p, \tag{2}$$

where $g_j(x)$ are the constraint functions, and $p$is their total number.

The constraints may be specified in terms of allowable stresses, strains, displacements, safety factors, limiting temperature, structural thickness, minimum or maximum fibre volume fraction, manufacturing requirements, and permissible cost. The laminate design rules must also be explicitly considered, including stacking-sequence symmetry and balance, restrictions on the number of consecutive plies with the same fibre orientation, and the requirement to ensure adequate interlaminar strength [1, pp. 69–70].

A relevant set of optimisation criteria and the corresponding design variables is summarised in Table 1.

Table 1

Main components of the multi-objective optimisation of a glass-fibre-reinforced composite

Parameter group	**Principal indicators**	**Optimisation direction**
Mechanical	strength, stiffness, impact resistance, fatigue life	maximisation
Weight and dimensional	weight, thickness, material consumption	minimisation
Manufacturing	porosity, impregnation quality, processing time, process stability	minimisation of defects and labour intensity
Operational	moisture resistance, thermal resistance, retention of properties, repairability	maximisation
Economic	cost of materials, manufacturing, inspection, and maintenance	minimisation
Environmental	energy consumption, waste generation, potential for reuse	minimisation of environmental impact

Source: developed by the author

Mechanical criteria should be determined not only from the nominal properties of an individual ply but also from the behaviour of the multilayer laminate. Fibre orientation provides high strength and stiffness primarily in the reinforcement direction, whereas the transverse and interlaminar properties depend largely on the polymer matrix and the condition of the fibre-matrix interface. Consequently, increasing the proportion of longitudinally oriented plies may improve the load-carrying capacity in one direction while reducing resistance to transverse loading, torsion, or local impact.

When designing structures subjected to dynamic loading, the laminate architecture must also be optimised with consideration of its frequency and damping characteristics [3, p. 416].

Structural weight is another important criterion. Weight reduction can be achieved by decreasing the laminate thickness, locally redistributing the reinforcing plies, or increasing the fibre content in the most highly loaded regions. However, an excessive reduction in thickness increases deformability and susceptibility to local buckling and manufacturing defects. Weight minimisation must therefore be performed while simultaneously satisfying the strength, stiffness, and stability constraints.

The cost criterion should not be reduced solely to the price of the constituent materials. The total cost of a structure includes the preparation of the reinforcement, forming, polymerisation, machining, quality control, repair, and maintenance. The use of a less expensive material may require an increase in structural thickness or weight, increase labour intensity, and shorten the service life. Economic performance should therefore be assessed over the entire structural life cycle.

Manufacturing parameters must be incorporated directly into the optimisation problem because the properties of the manufactured component may differ substantially from the calculated values. Inadequate impregnation, porosity, fibre waviness, local thickness variations, and deviations in fibre orientation reduce strength and increase the variability of in-service properties. A design solution should therefore be assessed not only in terms of its nominal performance but also in terms of its reproducibility under the selected manufacturing process. In the manufacture of glass-fibre-reinforced components, multi-objective optimisation of the processing parameters enables the simultaneous reduction of shrinkage, warpage, and dimensional variability [5, p. 41].

A multi-objective formulation generally does not yield a single solution that provides the best values for all performance indicators simultaneously. The Pareto-optimality principle should therefore be applied to identify a set of acceptable alternatives. A solution is considered Pareto-optimal if no criterion can be improved without deteriorating at least one other criterion. The set of such solutions forms the Pareto front, which represents the available trade-offs among the objective characteristics.

For example, when weight and cost are minimised while fatigue life is maximised, one design may have the lowest weight but a higher cost, another may provide a lower cost at the expense of increased material consumption, and a third may achieve greater durability with moderate values of the remaining characteristics. The final selection is made with consideration of the intended structural application, the consequences of potential failure, manufacturing capabilities, and established priorities.

The general framework of the proposed concept is presented in Fig. 1.

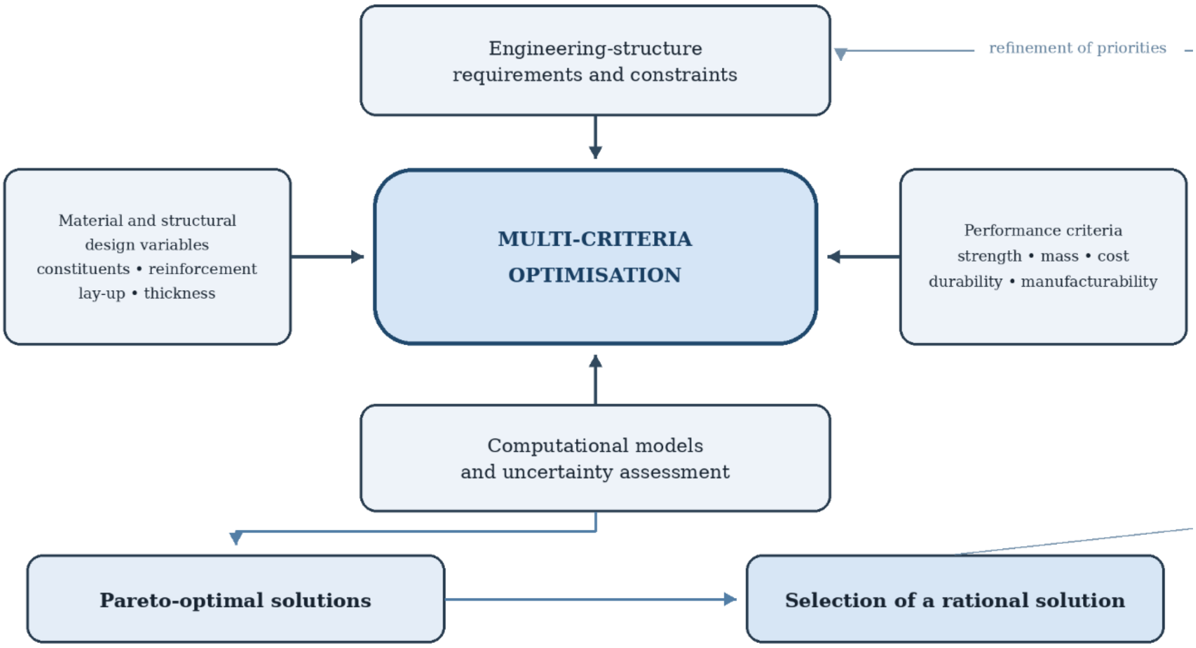

Fig. 1. Conceptual framework for the multi-objective optimisation of glass-fibre-reinforced composites for mechanical engineering applications

Source: developed by the author

Once the set of Pareto-optimal alternatives has been generated, the solution that best satisfies the requirements of the specific mechanical engineering structure must be identified. For this purpose, the individual criteria should be expressed in dimensionless form and combined into an aggregate performance measure:

$$Q_{(x)} = \sum_{i=1}^{m} w_i \, f_i(x) \tag{3}$$

where $Q_{(x)}$ is the aggregate performance measure of the design solution; $f_i(x)$ is the normalised value of the *i-th* criterion; w_i is the weighting coefficient assigned to the corresponding criterion; and m is the number of criteria.

The weighting coefficients represent the relative importance of the individual criteria and must satisfy the following condition:

$$\sum_{i=1}^{m} w_i = 1, w_i \geq 0 \tag{4}$$

Normalisation is required because weight, cost, strength, durability, and manufacturability have different units of measurement and numerical ranges. All criteria must also be expressed in a consistent direction of optimisation. The weighting coefficients are determined in accordance with the design specification, the functional purpose of the component, and the potential consequences of its failure. For safety-critical structures, priority should be given to strength, durability, and consistency of properties; for moving components, to minimum weight; and for serial production, to manufacturing cost and manufacturability.

The weighting coefficients should be varied across several design scenarios. One scenario may prioritise mechanical reliability, another may focus on minimising weight or cost, and a third may provide a balanced representation of all criteria. Comparing the results makes it possible to determine the sensitivity of the selected solution to the specified priorities. However, relying solely on an aggregate performance measure may result in the loss of certain Pareto-optimal alternatives. It is therefore advisable first to generate a set of compromise solutions and subsequently use the weighting coefficients to rank them.

The optimisation method should be selected according to the number and types of variables, the form of the objective functions, and the complexity of the computational model. Gradient-based methods may be used for problems involving a limited number of continuous parameters. Although these methods exhibit high convergence rates, they require smooth objective functions and may identify only a local optimum.

For the optimisation of glass-fibre-reinforced laminates, algorithms capable of handling continuous and discrete variables simultaneously are more appropriate. These include genetic algorithms, particle swarm optimisation, and differential evolution. Such methods do not require the derivatives of the objective functions, can be applied to complex feasible design spaces, and enable the generation of a set of solutions distributed along the Pareto front [7].

The application of these algorithms requires repeated evaluation of structural performance. For each combination of parameters, the stress-strain state must be determined, strength criteria verified, and weight, cost, manufacturability, and durability assessed. If each evaluation is performed using a detailed finite element model, the computational cost increases substantially.

The computational model must represent the anisotropic properties of the plies, reinforcement orientation, interlaminar interactions, boundary conditions, and the nature of the external loading. At the initial design stage, simplified shell models may be employed because they provide sufficient accuracy at a comparatively low computational cost. Once the design space has been narrowed, the selected alternatives should be verified using more detailed three-dimensional models.

When evaluating laminate strength, the failure mechanisms of the fibres, matrix, and interlaminar interfaces must be distinguished. The use of an equivalent stress measure alone does not adequately characterise the limiting state of a composite. Design alternatives should therefore be evaluated using criteria that account for fibre tension and compression, matrix failure, shear, and interlaminar delamination. For structures subjected to cyclic loading, damage accumulation and the progressive reduction in stiffness must additionally be assessed.

Computational costs can be reduced through surrogate models developed from a limited number of numerical simulations or experimental tests. Once the relationships between the input parameters and structural performance characteristics have been established, the surrogate model can be used to evaluate a large number of design alternatives rapidly, without repeatedly performing a complete finite element analysis [11].

Response surfaces, Gaussian processes, and artificial neural networks may be employed as surrogate-modelling techniques. The selection of a particular method depends on the amount of available data, the number of variables, and the nature of the relationships under consideration. For a relatively small number of parameters and smoothly varying responses, polynomial response surfaces may provide sufficient accuracy, whereas machine-learning methods are more appropriate for complex nonlinear relationships [6].

The accuracy of the surrogate model must be verified using data that were not employed during its development. Particular attention should be given to regions near limiting states and the Pareto front, since prediction errors in these regions may alter the ranking of design solutions. If the model accuracy is insufficient, the dataset should be supplemented with additional design points located in the regions containing the most promising solutions or exhibiting the greatest uncertainty.

Consideration of input-parameter uncertainty is an essential component of the proposed framework. The actual properties of a glass-fibre-reinforced composite differ from their nominal values because of constituent-property variability, porosity, non-uniform impregnation, and deviations in laminate thickness and fibre orientation. Under actual operating conditions, loads, temperature, humidity, and service duration also vary. Consequently, a solution that is optimal for nominal parameter values may prove insufficiently reliable once the structure has been manufactured.

The uncertain parameters can be classified as material, manufacturing, operational, and model-related. Material uncertainties include the elastic moduli, constituent strength, and interlaminar bond strength. Manufacturing uncertainties encompass deviations in thickness, fibre volume fraction, fibre orientation, and polymerisation conditions. Operational uncertainties are associated with variations in loading and environmental conditions, whereas model uncertainty arises from simplifications adopted in the computational model and the limited accuracy of failure criteria.

The influence of these parameters should be evaluated by means of sensitivity analysis. This makes it possible to identify the variables that exert the greatest influence on structural strength, stiffness, weight, durability, and cost. Parameters with a negligible effect may be fixed at acceptable values, whereas justified tolerances and enhanced manufacturing control should be established for the most influential parameters.

The results of the sensitivity analysis provide the basis for developing a robust design solution that retains acceptable performance despite possible variations in material properties, manufacturing conditions, and applied loading. Such a solution may be slightly inferior to the nominal optimum in terms of weight or cost; however, it will exhibit lower variability in its properties and a reduced probability of violating the specified constraints.

For example, a laminate of minimum thickness may satisfy the strength requirements at the nominal material properties but become unfit for service because of a minor deviation in fibre orientation or a reduction in fibre volume fraction. A slightly thicker laminate with a balanced architecture will have a greater weight but retain its load-carrying capacity over a wider range of manufacturing and operational deviations. Under such conditions, the latter design should be regarded as the more rational solution.

The manufacturability of the optimised architecture must be considered separately. A mathematical algorithm may generate a complex stacking sequence involving numerous changes in fibre orientation, local thickness transitions, and minor differences between adjacent plies. Although such an architecture may theoretically provide high performance, its manufacture may be associated with increased labour intensity, a greater probability of errors, and inconsistent properties. The assessment of manufacturability should encompass not only composite forming but also the subsequent processing of the finished component, whose parameters affect dimensional accuracy, surface roughness, and the probability of local damage [8].

Manufacturing rules must be incorporated directly into the system of constraints. These may specify permissible fibre-orientation angles, the maximum number of consecutive plies oriented in the same direction, the allowable rate of thickness variation, and laminate-symmetry requirements. The available forming process, the feasibility of automated lay-up, the characteristics of the manufacturing equipment, and the polymerisation conditions must also be considered.

A rational design must ensure not only the feasibility of manufacturing an experimental specimen but also the consistent reproduction of its properties in serial production. Therefore, a design in which a minor deviation in processing conditions causes a substantial deterioration in mechanical properties cannot be regarded as sufficiently effective, even if its nominal performance is high.

The consideration of in-service durability constitutes another important aspect of the optimisation process. The properties of glass-fibre-reinforced composites gradually deteriorate under cyclic loading, moisture absorption, temperature fluctuations, ultraviolet radiation, and exposure to aggressive environments. Consequently, comparing alternatives solely on the basis of their initial strength does not provide a comprehensive assessment of their suitability for long-term service.

Higher initial strength does not necessarily correspond to a longer service life. Increasing the fibre volume fraction enhances longitudinal stiffness but may impede impregnation, increase porosity, and reduce interlaminar strength. Reducing the number of transversely oriented plies may decrease structural weight but increase sensitivity to impact loading and torsion [9]. Durability assessment must therefore account for the interaction among the different degradation mechanisms.

Economic efficiency should be assessed over the entire product life cycle. In addition to material and manufacturing costs, the analysis must include the costs of quality control, maintenance, repair, equipment downtime, dismantling, and disposal. A design with a higher initial cost may be more economically advantageous if it provides lower weight, a longer service life, and reduced maintenance expenditure.

Environmental criteria may include manufacturing energy consumption, waste generation, repairability, and the potential for material reuse. Reducing structural weight decreases energy consumption during machine operation; however, a complex multicomponent composition may complicate the subsequent recycling of the product. This creates an additional trade-off that must be considered when generating the set of Pareto-optimal solutions.

The optimisation results must be verified at the mathematical, computational, and experimental levels. The first stage involves verifying constraint satisfaction, result stability, and convergence of the search algorithm. The second stage assesses the accuracy of the numerical model at different levels of finite element mesh refinement and using different laminate-modelling approaches. The final stage comprises experimental validation of the properties of the material, structural elements, or full-scale component.

Experimental validation should cover the characteristics employed as optimisation criteria or constraints, including stiffness, strength, ultimate load, impact resistance, fatigue life, and residual strength after environmental exposure. The actual laminate thickness, fibre volume fraction, porosity, and fibre orientation must also be monitored.

If the experimental results do not agree with the calculated values, the material properties, boundary conditions, failure criteria, or manufacturing tolerances must be refined, after which the optimisation procedure should be repeated. The proposed framework is therefore iterative: the results of the computational search are subjected to manufacturing and experimental verification, while the model parameters and feasible design space are progressively refined.

The final selection of the composite should not be based solely on the best value of the aggregate performance measure. The distance of the solution from the constraint boundaries, its sensitivity to variations in the weighting coefficients, and its robustness with respect to input uncertainty must also be assessed. Preference should be given to alternatives that retain acceptable performance under several operating scenarios and different combinations of design priorities.

Thus, the multi-objective optimisation of glass-fibre-reinforced composites should be implemented as a closed-loop computational design process. Within this process, product requirements are linked to material selection and reinforcement architecture; numerical simulation results are used to generate a set of Pareto-optimal solutions; and the final design is selected with consideration of manufacturability, uncertainty, life-cycle cost, and experimental validation. This approach enables the systematic design of mechanical engineering structures with a specified balance among mechanical performance, weight, cost, durability, and environmental impact.

Conclusions. Thus, multi-objective optimisation of glass-fibre-reinforced composites enables the coordinated consideration of mechanical performance, weight, cost, manufacturability, durability, and environmental impact. The proposed framework involves generating a set of Pareto-optimal solutions and evaluating them with regard to parameter uncertainty, manufacturability, and life-cycle cost. This provides a substantiated basis for selecting the composite architecture in accordance with the intended application and operating conditions of the mechanical engineering structure.

Further research should focus on developing methods for determining weighting coefficients, improving durability models for glass-fibre-reinforced composites, and experimentally validating the resulting optimised designs.

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