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Materials selection combined with optimal structural design: concept and some results

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Abstract

Some ideas on the place and role of structural optimization in combination of a materials selection procedure are presented. A side rocker beam of a DutchEVO car (multidisciplinary design project of a concept car at Delft University of Technology) is considered as a case study. A structural optimization system based on the Multipoint Approximation method (MARS) and MSC.MARC FEA code is employed. The developed technique is used to investigate the possibility to use natural fiber composites for a given structural component instead of some conventional (steel, aluminum alloy) and non-conventional (metallic and synthetic fiber composites) materials. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Material selection; Structural optimization; Natural fiber composites

1. Introduction

According to one of the definitions of sustainability, the sustainable development of human society presupposes, among other challenges, an ecological development, in other words, the development with special care of environmental resources [1]. This concerns also the engineering design, which should be based not only on the requirements on safety, but also on environmental aspects of product manufacture, use and disposal [2]. There are several ways to approach environmentally friendly design, namely, the design for recyclability, for minimal energy consumption, for minimal weight, for reducing air and water pollution, the gradual substitution of non-renewable materials by renewable ones, etc. These are mostly the optimization problems that are often connected to the philosophy and methods of material selection. In other words, optimal material selection in product design is one of the ways of approaching the sustainability in the modern society development.

The results presented in this paper have been obtained within the framework of a multidisciplinary project at Delft University of Technology. The DutchEVO project has been initiated as a part of Delft Interfaculty Research Cooperation (DIOC) program ‘Smart Product Systems’ in order to stimulate innovative, multidisciplinary research. The purpose of the project is to develop a knowledge base for sustainable product design. A sustainable car, in accordance to DutchEVO project task, means an environmentally friendly, affordable, lightweight car satisfying all current and/or future legislations on safety, emissions, recyclability, etc. Among the ways to reach the objective of the project, the development of the advanced methodology of lightweight design is expected to be the most valuable approach. This methodology can be based on optimal material selection with respect to minimum weight. Moreover, if materials selection is included in the procedure then new types of structural materials can be considered as candidates to be used for car components, e.g. renewable or partly renewable materials, such as composites containing natural fibers and/or natural matrix. A compound objective function is suggested to assist a designer in the final decision. This allows one to include the environmental aspects into the procedure of material selection as parts

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of the compound objective function under the condition that they are described numerically (eco-points from life cycle analysis (LCA), for example). The suggested approach is based on well-developed techniques that are united in one system allowing one to solve the problem of material selection based on thorough mechanical analysis of a structural component.

The structure of the paper is the following: the basis of the proposed approach with short overview of material selection methods; description of a case study; results of preliminary material selection; description of the structural optimization technique; comparison of the materials series obtained via different formulation of material indices and the developed approach. The assessment of the natural fiber composites applicability in heavily loaded and less loaded structure of a given component is also discussed.

2. Basis of the developed approach

From an engineering viewpoint, material selection is a process aimed at the identification of materials which after appropriate manufacturing will have the dimensions, shape and properties necessary for the product or component to demonstrate its required function at the lowest cost [3]. In this definition of material selection by Gutteridge and Waterman it is easily seen that the process of material choice is accompanied by some constraints, i.e. certain geometry, required properties and low cost. In other words, the idea of material selection is always to reach the optimal solution of the optimization problem that is formulated in terms of objective and constraint functions under a number of design variables within corresponding side limits. In the case of a multi-objective definition of optimal material selection, it is often not possible to reach the optimal values of all objectives simultaneously, and only a compromise solution is feasible [4]. According to Ashby, the goal of choosing a material is to optimize a number of metrics of performance in the product in which this material is used. Common among these metrics are cost, mass, volume, power-to-weight ratio, energy density, and there are many more other characteristics that can be in conflict with each other. Special methods based on optimization or decision-making theories can be employed to solve this kind of conflicts. The optimization problem should be formulated as correct as possible, because the accuracy of the solution of the optimization problem depends rather on formulation than on the employed method. We will show in following sections how the result of material selection varies depending on problem formulation.

In order to provide an optimal material selection in single- or multi-objective formulation, an optimization method alone is insufficient to solve the problem; the systemized information on available engineering mate-

rials is required. During recent decades it has been accepted that the information on engineering materials can be presented in two categories: data and knowledge, even if the distinction between a knowledge base and a database is still unclear [5]. ‘Data’ are defined as the result of measurements that can be presented in numbers, whereas ‘knowledge’ represents the connections between items of data and is mostly expressed in plain language. According to these categories there are two possibilities to maintain the process of material choice, via material databases or knowledge-based systems (KBS). The former contain information on engineering materials, and the best form of their presentation is a computerized database that provides easy access to the materials’ data. The latter comprise expert knowledge capable of assisting the user in an interactive way to solve various problems and queries. The review of both possibilities can be found elsewhere [6]. The simplest form of a materials database is the data in handbooks on engineering materials containing mechanical, physical, chemical properties. More sophisticated databases are presented by computerized systems which sometimes form material selection packages. It is worth mentioning here the Cambridge Material Selector (CMS), that being broadened by additional features and databases on materials processing, yielded in the Cambridge Engineering Selector (CES) [7]. This tool for materials selection is flexible enough to construct performance indices and constraints in different combinations, has a very convenient graphical interface and, most importantly, contains vast materials databases. Performance indices and constraints for material selection depend on a problem formulation, i.e. the aim of material selection, a structural component function, possibility to manufacture, etc. In other words, the material selection via materials databases is a problem-dependent process. The materials selection using KBS seems to be also a problem-dependent process. It starts with the formulation of objectives and constraints that are then translated to heuristic rules. The rule-based technique ‘If-Then’ is implemented in KBS to perform the material selection. Presented in [8], KBS for material selection provides the connections not only to the material (polymer-based composites) database, but also to the KBS for design for cost (manufacturing cost is considered) and to the design analysis tool. Consequently, the KBS of such type can be employed, both in the concept and embodiment stages of design, the latter being accompanied by structural analysis. It is important to note that some assumptions concerning structural analysis are employed to derive performance and material indices also in the methodology proposed by Ashby [7], but these assumptions are valid for limited number of load cases, boundary conditions, and material behavior models. For example, these indices do not take into account the situation when structure buckles. In this case a designer

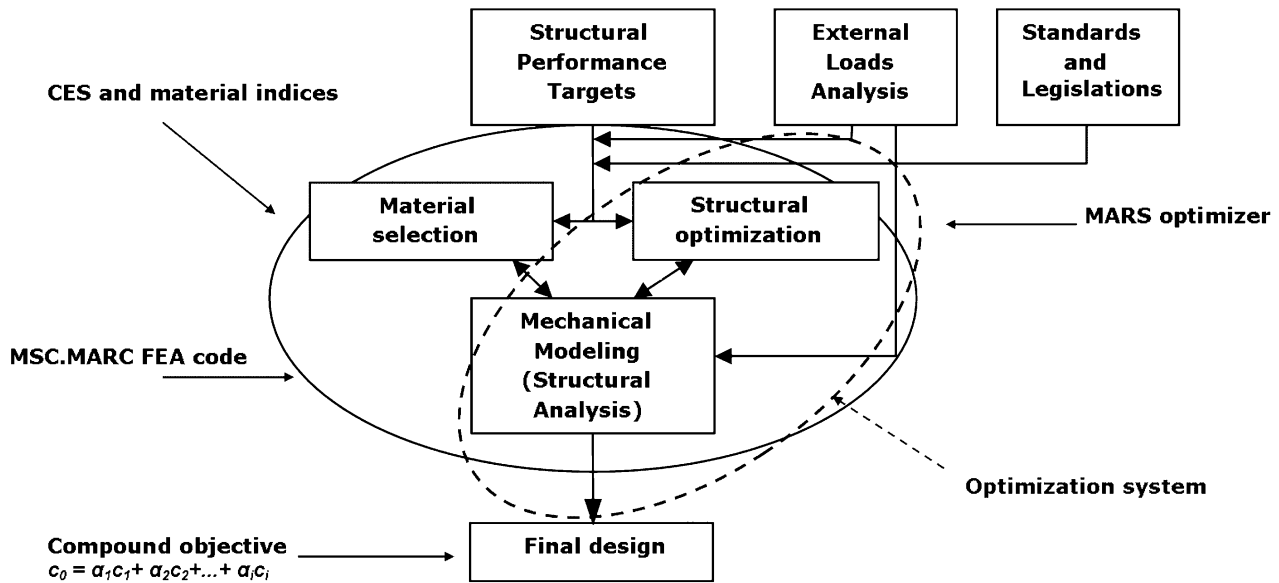


Fig. 1. The developed approach.

needs more valid methods of mechanical analysis of the designed component.

To conclude the short review on existing (or visible in future) tools for material selection, it is possible to line them up in series with respect to the increasing degree of accuracy of taking into account the mechanical behavior of a structural component. The first one, as the most simple, is material data on standard mechanical properties that designer can find in handbooks, etc. Then, the computerized databases accompanied by samples of material strength theory (simple structures and load cases), like CES, can be considered. KBS is at the following step of the improvement of material selection procedure, because it contains not only computerized material databases but also expert knowledge and, in addition, can provide links to structural (stress–strain) analysis of the component.

The next step in improving the process of material selection in the part of structural analysis can be the combination of material selection and structural optimization. Nowadays, structural optimization is employed in the design process mainly in the stage of detailed design, when the material, manufacturing process and basic dimensions are determined. This paper suggests the material selection in combination with structural optimization procedure. As noted in Section 1 we employ well-developed techniques and organize them in one system that allows solving the problem of material selection based on thorough structural analysis of a component. In other words, each material-candidate shows its best potential in mechanical behavior under given load and boundary conditions. It makes sense if several modes of material resistance are taken into

account, e.g. buckling accompanying other mechanical constraints on design.

The scheme of the developed approach is given in Fig. 1. It should be noted that the procedure is problem-dependent and a component (or group of structural components) should be assigned beforehand. Material and performance indices are derived on the basis of performance targets, requirements of the standards and legislations and external loads analysis. CES is employed for preliminary material selection. In order to perform structural optimization of chosen component, an optimization system was constructed on the basis of the Multipoint Approximation method with Response Surface fitting (MARS) combined with MSC.MARC FEA code [9]. Because the material selection is considered here as a multi-objective optimization we use a compound objective function in the following form:

$$c = \alpha_1 c_1 + \alpha_2 c_2 + \dots + \alpha_i c_i + \dots + \alpha_n c_n \quad (1)$$

where α_i and c_i are weight coefficient and material (or performance) index, respectively, for i -th objective, $i = 1, \dots, n$. It is better to derive indices in dimensionless form (normalized, e.g. to the reference material) in order to avoid the use of so-called 'exchange constants' which have been formulated in [4]. One should be aware only that the sum of weight coefficients is equal to unity. In this paper we consider only mass and cost index, but the form of the compound objective function allows one to include other requirements applied to the component. These might be environmental impact factors, cost for recycling, etc., if they can be presented in some numbers. The final choice of optimal material can be made then on the base of minimization or maxi-

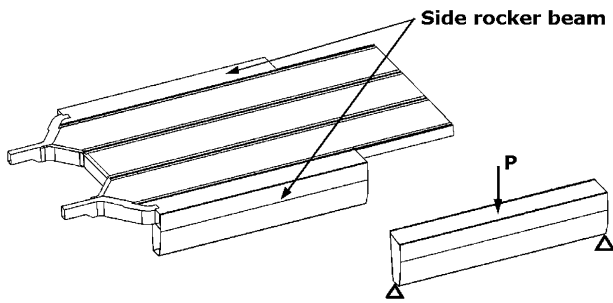


Fig. 2. DutchEVO car bottom structure and chosen case study. P is the design load.

zation of the compound objective function depending on the problem.

3. Case study

The DutchEVO car project started with the evaluation of a design baseline, factors that can be improved in order to avoid ‘unsustainabilities’, and potentials of integrated multidisciplinary research. As a result, a hierarchy for design of the DutchEVO car was determined. Low mass of the car appeared to be at the highest level of this ladder of design priorities [10]. One of the design possibilities for the DutchEVO car, which is considered as advantageous for the car structure, helping to solve the ‘safety—lightweight design’ conflict, is the raised floor concept. Large rocker beams on both sides of the car floor are required to absorb the side impact energy at the level of other cars’ bumper. This concept developed later into the type of a platform structure for the car body when the bottom part of a car carries the main loads. This also gives the possibility to use non-conventional (light, renewable) materials for the upper part of bodywork in less loaded substructures. An additional weight decrease could be expected in this case. A side rocker beam, considered as the main load-carrying component of the bottom structure, was chosen as a case study (Fig. 2).

The design load applied to the case study results from the automotive standards on overall bending stiffness of load-carrying automotive body parts. Side impact resistance of the rocker structure is outside the scope of this paper and is discussed in [11]. Geometry of the rocker beam is given by design constraints and is represented by a hollow, rectangular cross-section. The finite element model of the rocker beam and the validation of boundary and load conditions is given in [12]. The mechanical performance of the beam of given geometry under the bending stiffness requirement calls for an additional demand of geometrical stability (non-buckling behavior) of beam walls. We also included into consideration the requirement on maximum equivalent stresses. Thus, the optimal design of the chosen case study is performed

under the bending stiffness, strength and buckling constraints.

4. Materials

4.1. Preliminary materials selection

Preliminary material selection was done with the help of CES, product of Granta Design Ltd. This selector is based on the graphical engineering selection methodology developed by M. Ashby and co-workers at Cambridge University, UK [7]. It integrates the selection of optimal material and the best manufacturing process route. CES contains extended database on materials, references, links, etc. The CES methodology provides designers with so-called material indices which depend on the performance of a given detail and the objectives of optimal material selection. In the case of lightweight design of a stiff and strong beam, the recommended material indices are $E^{1/2}/\rho$ and $\sigma^{2/3}/\rho$ (E is the Young’s modulus, ρ is the material density, and σ is the stress at the tension site of the beam).

The first round of the preliminary selection was performed using the evaluation version of CES package. The procedure was based on the above-mentioned indices and limited values of Young’s modulus, fracture toughness and a material price per kg. Four stages of the selection were executed and their intersection was considered as the result of the first round of the materials choice [12].

The second round of material selection was done using the educational version of CES through two and three graphical stages. The first two stages were based on material index for a light and stiff beam, fracture toughness and material price. The third one included the environmental aspects of design: recycle fraction and energy content. The summary information on the structural materials that passed the stages of the selection in both rounds is given in Table 1.

The difference between the results of the first round and two stages of the second round selection might be explained by the recall ratio of materials databases in different types of CES packages. If the user has a commercial version of the selector, or maybe, version aimed at the material selection in a particular industrial branch, then the choice can be more specific. For the purpose of this paper, the recall ratio of the considered materials databases is sufficient enough to show how the procedure can be constructed and used. The third stage of the second round devoted mainly to the requirement of the recyclable material fraction. A relatively high value of recycle fraction of approximately 0.8 was considered. This value yields from the discussions on environmental regulations for future automotive design in the European Union. It is easy to see that the

Table 1
Results of material selection via CES

Material	First round	Second round: stage 1	Second round: stage 2	Second round: stage 3
Alumina particulate reinforced Al	+	+	+	–
Aluminum/iron composite	+	+	+	–
Aluminum/silicon carbide Composite	+	+	+	–
Cast aluminum alloy	–	+	+	+
Cast magnesium alloy	–	+	+	–
Epoxy/glass fiber composite	+	+	+	–
High density wood (longitudinal)	–	+	+	–
Wrought aluminum alloys	+	+	+	+
Wrought magnesium alloys	+	+	+	+

recyclability being included into the scope of requirements can leave virtually no choice for a designer.

Based on the results of the first round of material selection (see Table 1) we made the preliminary choice of material groups that were considered later as candidates for the DutchEVO car side rocker beam. We excluded from this group and added to it some of the materials. For example, aluminum/silicon carbide composite, according to the CES materials database, has a large range of price. Because of the price variety, non-comparable with the other resulting materials, we excluded this material from consideration. Epoxy/glass fiber composite was substituted by a composite of epoxy matrix reinforced with carbon fibers because of availability of the mechanical properties of the material suitable to produce the hollow, rectangular beam with thin walls and covers, in other words under the consideration of technology that can be applied to provide specific mechanical behavior of the beam of prescribed geometry [12]. The properties of such a composite material should be at least the same in different directions of the plane. They are allowed to be different from the properties in the plane only through the thickness of the composite plate. Medium carbon steel has been included into consideration as a reference material. Thus, the following materials were chosen as the first group of candidates for the case study structure:

- medium carbon steel;
- alumina particulate reinforced aluminum;
- aluminum/iron composite;
- epoxy/carbon fiber composite;
- wrought aluminum alloys; and
- wrought magnesium alloys.

4.2. Natural fiber composites

As pointed out in Section 1, the gradual substitution of non-renewable by renewable materials can contribute to the sustainable development of the society. Natural

fiber composites are renewable or partly renewable materials, depending on the matrix. Fibers for such kind of composites can be derived from hemp, flax, jute, sisal, cotton and some other plant resources. Different plastics (thermoplastics or thermosets) can be used as a matrix. An epoxy, polypropylene (PP) and polyester are the most promising materials for matrices in structural composites.

The main advantages of natural fiber composites are their low weight and cost in comparison to other materials. They can be easily disposed at the end of life cycle, and in addition, without environmental damage.

The disadvantages of natural fiber composites with respect to structural design are, first of all, relatively low mechanical properties, which, furthermore, are sensitive to service conditions, such as humidity and temperature. The mechanical properties of natural fibers also have large scatter due to the growing conditions of plants and subsequent storage of raw material and fibers.

The first applications of this group of materials in the automotive industry have been aimed at the substituting synthetic composites (glass or carbon fiber composite, etc.) in non-loaded or lightly loaded interior parts, such as door trim panels (PP/flax, polyurethane/flax, in A-Class Mercedes Benz), rear shelf trims (PP/flax, Chevrolet), trunk trims (Daimler-Benz), dashboard (Daimler-Benz), seat squabs, mats and panels (combination of natural fibers, Ford Motors Company) and some others. There are also known exterior applications of natural fiber materials, for example an underbody paneling and the covers of motor and gearbox (PP/flax in A-Class Mercedes Benz) [13,14].

The natural fiber composites application to medium and heavily loaded structures will be possible through the improvement of their mechanical properties, reliability of mechanical testing results, proper material models for numerical simulation of structural behavior and the development of design guidelines [10]. For example, the use of special chemical treatment based on

modifiers or compatibilizers makes the adhesion of the fiber and the matrix better that improves the mechanical properties of the composite.

In the current paper, in addition to more or less conventional materials selected as the first group of candidates for DutchEVO side rocker beam, we evaluate the composites reinforced by randomly distributed non-modified natural fibers. PP matrix was chosen as the most usable in automotive applications. A PP/glass fiber composite was considered for comparison. Thus, the second group of material-candidates is:

- PP/glass fibers (40%)¹, [15,16] and CES database;
- PP/flax fibers (30–40%), [16–19];
- PP/hemp fibers (40%), [16–18,20];
- PP/jute fibers (40%), [16–18,21–23];
- PP/sisal fibers (40%), [16–18,21,24]; and
- PP/kenaf (40%), [17,25].

The mechanical properties for the most of the composites were averaged over the data taken from the references given above. In addition, the properties of a PP/flax (30% mass fraction) composite produced by SYMALIT GMT were experimentally obtained in our laboratory according to the ISO527-1 standard. Several of these properties were presented in [26]. The mechanical properties of a PP/hemp fibers composite have been estimated based on the following assumptions: (a) the considered composites have the same distribution of fibers in the matrix; (b) the fibers are of the same aspect ratio; and (c) they have the same characteristics of adhesion with the PP matrix. The density of the composites was calculated using the mixture rule based on the corresponding data on fibers and PP matrix from CES database and other sources [15,16].

5. Structural optimization

5.1. Formulation of the optimization problem

A structural optimization problem for the case study under consideration is formulated here as follows:

- minimize mass of the beam under the constraints of bending stiffness, strength and buckling; the beam is considered simply supported at both edges, loaded in the mid-span, and has a hollow rectangular cross-section (see Fig. 2);
- design variables are: the wall and cover thicknesses, the depth and width of the beam;
- side constraints are limited only by structural geometry (neither technological nor manufacturability aspects are taken into account).

The mathematical formulation of this optimization problem one can find in [9] along with the values of

¹ Here and below the fiber volume fraction is shown in parentheses, if the other is not mentioned.

design load and side constraints. We would like only to mention here that for each design point the maximum values of deflection, stresses and lowest critical load, that are needed to calculate constraints, result from the mechanical behavior analysis, FEA in our case.

The Multipoint Approximation method based on Response Surface analysis (MARS) [27] was used as the structural optimization tool. This optimization technique is based on approximations of objective and constraint functions in specially or randomly distributed points of a design space. The random plan of numerical experiments gives the advantage of performing a continuous procedure even if there is no solution in one or several points of the design space. This situation often occurs during the FEA when structure buckles and FE program terminates with wrong exit number. The MARS technique skips this point and searches for the nearest point where the solution exists. The structural optimization is an iterative process, which stops when one of the termination conditions occurs. The MARS programming code² contains the common type of approximations: linear, multiplicative and reciprocal. In order to reduce the computational time, we implemented the mechanistic approach to develop simplified approximations of the constraint functions. It was shown in [9] that if the mechanical behavior of an optimized structure, or the parts of this structure, can be even approximately described by engineering equations then mechanistic approximations can be easily derived and applied to corresponding mechanical constraints. In this case the convergence of the optimization procedure needs a fewer number of iterations and, hence less structural analysis calculations. The mechanistic approximations derived for the considered structure reduced the number of FEA runs by three to four times.

5.2. Construction of the optimization system

In order to solve the optimization problem, we developed an optimization system [9] using an optimization code that was linked to analysis software and, therefore, the whole system combined three following parts: optimization programs (optimizer), problem-dependent analyzer and interface programs that connected the optimizer with the analysis software. These interfaces depend on the structure of the analysis code and have to be created for each specific application. The MSC.MARC FEA code provides a user subroutines feature, which allows users to substitute their own subroutines for those existing in the program [28]. It sufficiently simplifies interface programming and makes the MSC.MARC FEA code attractive to user willing to interfere in the calculation process. Several user subrou-

² The MARS optimizer code was kindly provided by V.V. Toropov (Bradford University, UK) for this project.

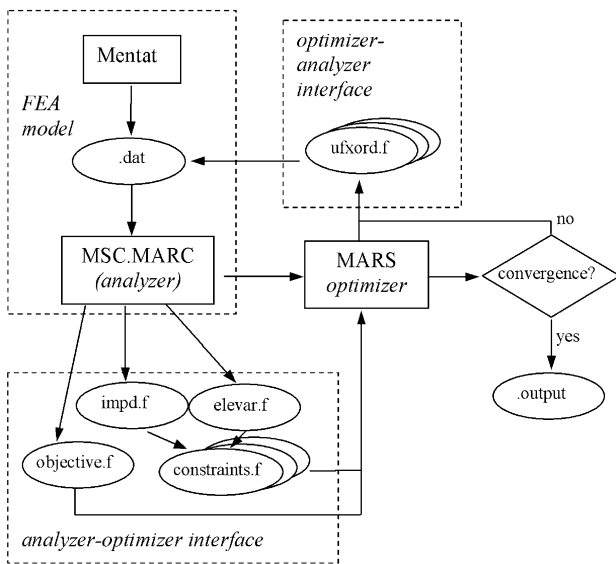


Fig. 3. The MARS optimization system.

tines were employed, such as ‘impd.f’, ‘elevat.f’ and ‘ufxord.f’. They allowed us to get necessary information for particular nodes and elements and, in addition, to re-mesh the model in accordance with the geometry of each new design. All programs: optimizer, analyzer and interfaces, were combined in MARS optimization system via ‘start_optimization.bat’ file to start the optimization procedure. A scheme of the developed optimization system is shown in Fig. 3.

5.3. Results of structural optimization

The optimal design of the given case study has been performed using the developed optimization system for two load cases: (1) the side rocker beam is considered as a main structure providing the necessary bending stiffness of an entire bodywork; and (2) the bending stiffness is provided by the bottom structure, the side rocker beam only partly participates in overall bending resistance. In the latter case, the design load was reduced by 10 times. In the first load case the side rocker beam was considered as a heavily loaded structure, whereas in the second case as the less loaded structure (medium- or light loaded in dependence on load categories definitions).

Optimal design variables and the corresponding mass of the side rocker beam are given in Table 2 in accordance with optimal solutions obtained during the numerical calculations using MARS optimization system. One might notice that no optimal solution exists for the heavily loaded side rocker beam of PP composites reinforced with natural and even with glass fibers. These materials have low mechanical properties because of the random distribution of fibers in matrix. They could not provide the desirable bending stiffness under given limits on design space that resulted from the manufacturing constraints. The polymer products can be produced in limited thicknesses that are less than 5–6 mm.

A set of active constraints in optimal designs (see Table 2) differed with respect to the load case. This set

Table 2
The optimal solutions using MARS optimization system in case of heavily loaded (numerator) and less loaded structure (denominator)

Material (group of selection) ^a	Wall thickness (mm)	Cover thickness (mm)	Depth (mm)	Width (mm)	Mass (kg)	Active constraints ^b
Medium carbon steel (I)	1.28/1.00	1.67/1.20	244.5/200.0	135.0/135.0	21.086/14.190	1, 3/none
Wrought aluminum alloy (I)	2.10/1.30	2.28/1.30	339.8/200.0	135.0/135.0	14.498/6.184	1, 3/none
Wrought magnesium (I)	2.4/1.30	4.643/1.30	350.0/200.0	137.6/135.0	14.427/4.246	1, 3/none
Aluminum/Iron composite (I)	2.05/1.30	2.21/1.30	334.9/200.0	135.0/135.0	22.555/9.973	1, 3/none
Alumina particulate reinforced aluminum (I)	1.96/1.30	2.18/1.30	326.4/200.0	135.0/135.0	14.403/6.707	1, 3/none
Epoxy/carbon fiber composite (I)	2.46/1.30	3.54/1.46	311.6/200.0	135.0/135.0	9.951/3.656	1, 3/3
PP/glass fiber composite (40%) (II)	–/2.01	–/2.18	–/330.0	–/135.0	No optimal solution/7.989	–/1, 3
PP/flax (40%) (II)	–/2.34	–/4.05	–/350.0	–/135.0	No optimal solution/7.642	–/1, 3
PP/hemp (40%) (II)	–/2.22	–/2.52	–/350.0	–/135.0	No optimal solution/6.914	–/1, 3
PP/jute (40%) (II)	–/2.44	–/5.04	–/350.0	–/140.1	No optimal solution/9.165	–/1, 3
PP/sisal (40%) (II)	–	–	–	–	No optimal solution	–
PP/kenaf (40%) (II)	–/2.526	–/5.209	–/350.0	–/160.0	No optimal solution/10.665	–/1, 3

^a (I) corresponds to the first group (Section 4.1); (II) to the second group (Section 4.2).

^b 1 corresponds to the bending stiffness; 2 to the strength (inactive in all solutions); 3 to the buckling constraint.

Table 3
Input data for materials indices

Material	Young's modulus (GPa)	Density (kg/m ³)	Price (Euro/kg)
Medium carbon steel	210	7840	0.572
Wrought aluminum alloy	70	2840	1.750
Wrought magnesium	42	1950	2.273
Aluminum/Iron composite	74.4	4580	4.085
Alumina particulate reinforced aluminum	81	3080	5.719
Epoxy/carbon fiber composite (60%)	69 (longitudinal)	1600	14.742
PP/glass fiber composite (40%)	7.75	1670	1.436
PP/flax (40%)	4.65	1199	0.903
PP/hemp (40%)	6	1236	0.860
PP/jute (40%)	3.96	1174	0.862
PP/sisal (40%)	1.61	1172	0.892
PP/kenaf (40%)	3.55	1242	0.860

is an indication of the involvement of a material in the resistance behavior in accordance to one or another mechanical constraint. For more or less regular structural materials with comparatively good mechanical properties (in our case they compile the first group of candidate materials) bending stiffness and buckling constraint were active for the heavily loaded side rocker beam whereas none of the considered constraints became active for the light loaded structure. An exception was the epoxy/carbon fiber composite structure in the light-load case when the side rocker beam was designed based on the structural stability behavior (buckling was the only active constraint). The second group of candidates showed the full participation in resistance to bending and buckling behavior for the light loaded case study. The résumé in general seems to be obvious if one takes into account the degree of material involvement in the resistance to applied load. Under the given conditions of optimization problem it is unreasonable to use the materials of high mechanical properties for the less loaded case study and the materials of low mechanical properties for heavily loaded structure. The application of the epoxy/carbon fiber composite to the case study structure is the most promising. This material has the Young's modulus that is comparable with aluminum alloys and, in addition, it is much lighter. If minimal mass is considered as the only criterion for the optimal material choice, then the epoxy/carbon fiber composite is the best candidate for the given structure under both considered load cases.

In Section 6 the importance of factors other than mass and mechanical behavior of structures, are discussed.

6. Comparison of different approaches

The purpose of the paper is to show how structural optimization can be employed during material selection, and what effect it gives in comparison with other material selection criteria. Therefore, all considered

materials were compared using: (i) some of the material indices provided for optimal material selection for samples of simple structures and load cases; and (ii) the developed approach based on the compound objective function introduced in Section 2.

We looked at the material indices for a light and stiff beam, $E^{1/2}/\rho$ (see Section 4.1), and for a light, stiff and cheap beam, $E^{1/2}/(\rho p)$; the latter takes into account also the price of the material, p . The input data for these indices are given in Table 3. The price of the PP matrix composites was calculated using the average data on the fibers and matrix from the CES database and other sources [15,16,19,29]. For steel and metallic matrix composites it was averaged based on the data of the CES database. The free market prices of aluminum and magnesium alloys were considered [30,31]. The price of epoxy/carbon fiber composite was evaluated based on the average price of matrix (CES database) and fibers produced by Zoltek Corporation [32]. Figs. 4 and 5 show the above indices for the considered materials. The larger these indices, then better the material to be used in the light and stiff or light, stiff and cheap beam.

The comparison of the obtained data on the material index for a light and stiff beam, $E^{1/2}/\rho$, (see Fig. 4) resulted in an epoxy/carbon fiber composite as the best material for the considered structure. Wrought magnesium and wrought aluminum alloy are the next candidates. This conclusion coincides with the results of the comparison of the materials by optimal mass for the light loaded rocker beam and is pretty close to the results for the heavily loaded beam (see Table 2).

If the materials price is included into consideration via the material index for a light, stiff and cheap beam, $E^{1/2}/(\rho p)$ (see Fig. 5), then steel remains the best choice as a material for the given structural component. However, as the next candidates, non-conventional composites can be considered: PP composites reinforced with hemp, flax, jute or kenaf fibers compete in this case with aluminum alloy.

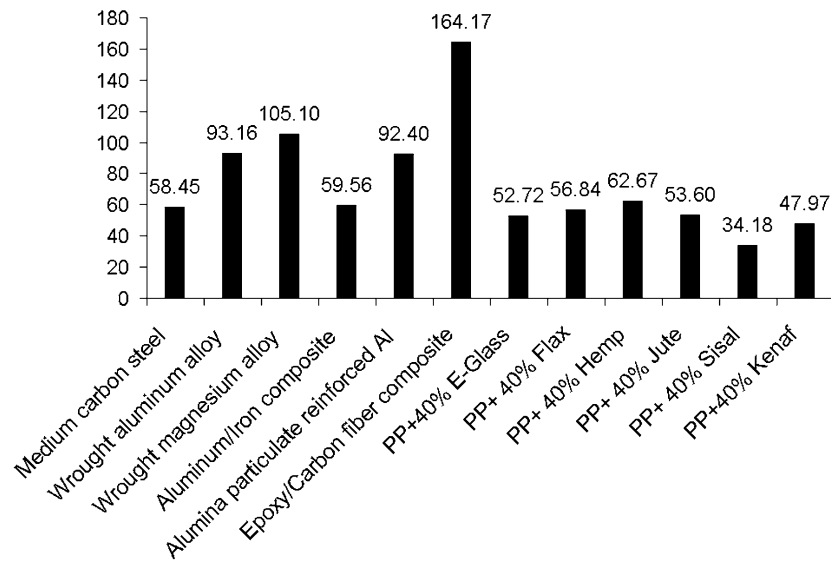


Fig. 4. Material index for a light and stiff beam.

The material selection based on the above material indices gives a result without the consideration of geometrical design constraints which, for example, depend on a material processability. Geometrical constraints in combination with the applied load and boundary conditions affect the involvement of the material in one or another mode of mechanical behavior, in other words, in the resistance to applied load. This also can play a significant role in optimal material choice.

The developed approach allows one to select the material in accordance with the thorough mechanical analysis of designed structure. For the given case study the category of the applied load is taken into account that makes possible to consider the capacity of load resistance of the structure leading to the optimal dimen-

sions. The compound objective in form of Eq. (1) includes two parameters for material selection discussed here, namely, the optimal mass under the correspondent load case and the price of the material, both normalized to steel as the reference material. The weight coefficients were taken rather ad arbitrium, i.e. 0.8 and 0.2, assuming that the mass is more valuable than the price. As mentioned in Section 2, other parameters can be also included into consideration on availability. They can contribute to materials choice via separate objectives of a multi-objective optimization problem or via constraints depending on the formulation of the problem of optimal material selection. The weight coefficients should result from the expert’s evaluation.

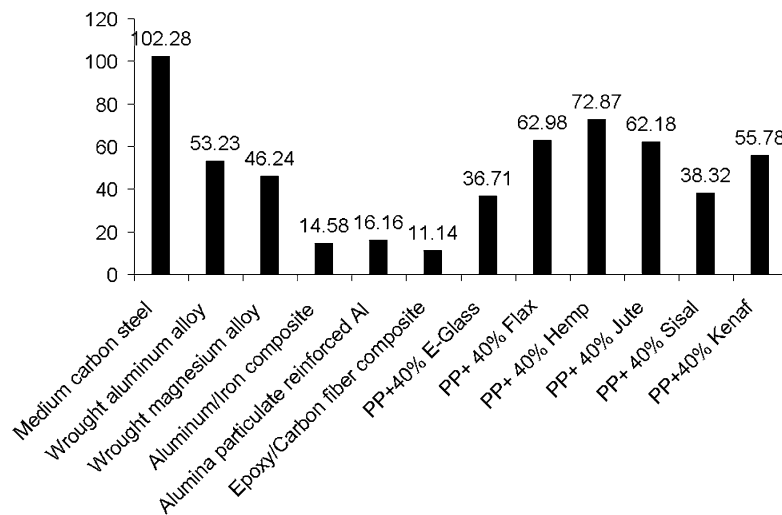


Fig. 5. Material index for a light, stiff and cheap beam.

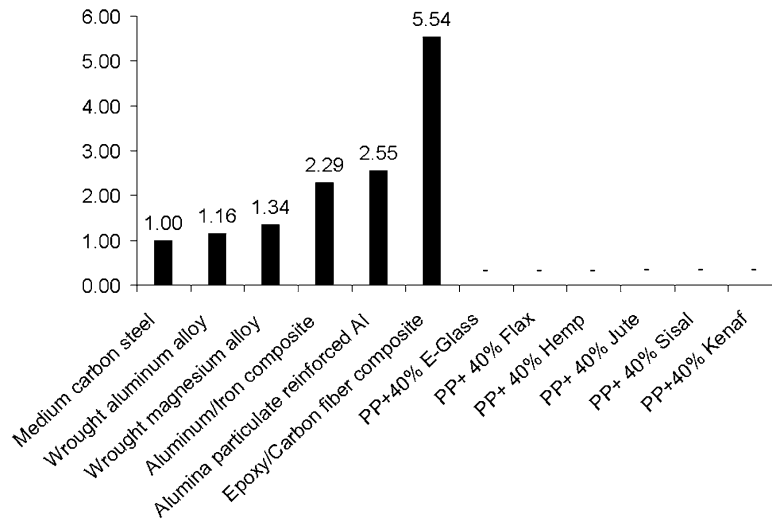


Fig. 6. Compound objective function for the heavily loaded structure.

The estimated data on compound objective are presented in Figs. 6 and 7. The minimum value of the compound objective function corresponds to the best material-candidate. As one can see in Fig. 6 it is steel for the heavily loaded side rocker beam. Wrought aluminum and wrought magnesium alloys are the next candidates. For light loaded beam (see Fig. 7) the sequence for material choice starts from a PP/hemp fibers composite following by PP composites reinforced with flax and jute fibers.

It is important to point out that the optimal material choice depends on the formulation of the problem as well as on the applied criteria and method. We can summarize our results as follows. Material selection based on indices gives an epoxy/carbon fiber composite as the best material for the light and stiff beam and a

medium carbon steel—for the light, stiff and cheap beam. The developed approach shows steel as the best candidate for the heavily loaded case study structure and a PP/hemp fiber composite—for the light loaded structure. This result can be different if one changes the weight coefficients showing the significance of separate objectives in multi-objective compound function and/or adds the other parameters that are also valuable for material choice, i.e. recyclability, manufacturability, crashworthiness, etc. For example, if the designer is restricted by the car component mass limit, say 15 kg for a side rocker beam in the case of a heavily loaded structure, due to the necessity to decrease the CO₂ emissions down to a certain level, then steel is out of consideration (see Table 2) and a wrought aluminum alloy can be named as the best candidate (see Fig. 6).

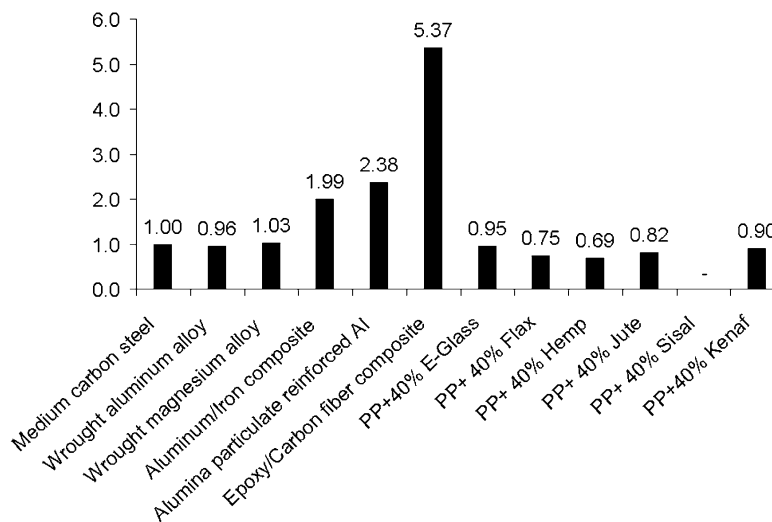


Fig. 7. Compound objective function for the light loaded structure.

7. Conclusions

The paper suggests the material selection in combination with structural optimization procedure. Employing the well-developed techniques we organized them in one system that allows solving the problem of material selection based on structural optimization including mechanical analysis of a component. In other words, the optimal material choice according to the constructed system is based on the best potential of each material-candidate in mechanical behavior under given load and boundary conditions. In order to show the advantage of the proposed procedure, the MARS optimization system was developed and applied to the design of the side rocker beam of the DutchEVO car with respect to the minimum mass under stiffness, strength and buckling constraints for two load cases (heavily and light loaded structure). The compound objective formulated here included optimal mass of the designed structure and the price of the corresponding material. Other parameters such as recyclability, manufacturability, LCA impact factors, etc., can be also included into consideration, if available.

Comparison of the results of the materials selection according to different approaches (via the material indices and the compound objective function) showed that the optimal material choice depends on the formulation of the problem as well as on the applied criteria and method. In addition, the possibility to use PP matrix composites reinforced by non-modified natural fibers in automobile structures was examined in comparison with the conventional (steel, aluminum alloy) and non-conventional (metallic and synthetic fiber composites) materials based on the given case study. The developed approach shows steel as the best candidate for the heavily loaded case study structure and a PP/hemp fiber composite for the light loaded structure. For heavily loaded structures oriented natural fiber composites might be feasible and will be the subject of further research.

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