CONSIDERATION OF MANUFACTURING ASPECTS IN STRUCTURAL OPTIMIZATION VIA KNOWLEDGE-BASED MODELS

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Abstract

Techniques are presented which allow to establish approximation models based on qualitative knowledge which then can be part of integrated design optimization models. So more complete overall models can be achieved which include aspects otherwise not considered. The approaches are mainly considered for use in earlier development phases with a lack of high fidelity models especially for manufacturing aspects. More hard data arising during the development process can then be relatively easily used to update the approximation models. This is shown for the simultaneous consideration of structural mechanics and manufacturing aspects of extruded stiffener aluminum profiles potentially also reinforced via steel ropes or carbon fiber ropes.

1. INTRODUCTION

The performance and cost of aerospace structures are mainly determined by decisions in early development stages [1]. Depending on the field of application, many disciplines may influence an optimal design also by economic considerations. For example, while automotive structures are mainly driven by crash loads and low cost bulk production, aeronautical structures are determined by function, life cycle loads, and smaller batch manufacturing processes. An optimal design for these structures which meets the requirements of different disciplines can be found by using the methods of multidisciplinary structural optimization [2]. While well known methods such as stochastic optimization algorithms [3], robust design [4], and approximation models [5] are applied in later product development stages, their use in early stages is often limited. One reasons for this is the lack of proper parameterized models especially for manufacturing aspects. On the other side, knowledge available could be “somehow” used to establish such models, which is the main objective of this paper.

For common manufacturing processes, broad information is available from test data such as shape distortion [6], producibility [7] and economic aspects. Newly developed manufacturing processes such as aluminum-steel composite extrusion [8] are less well known. Several techniques are used to consider manufacturing processes in structural optimization problems. Computationally costly numerical models [9] and empirical models from simulation and test data [10] are available to some extent. They still need an extensive data set to build the approximation model or to validate the simulation code respectively. To integrate manufacturing influences for which a few or no simulations and tests are available at least in a roughly estimated way Hajela [11], suggests the use of fuzzy logic [12] to include expert knowledge in the model. Natural language is utilized for parameterizations of so called Fuzzy Rule Based Systems (FRBS) and ‘if … then’ rules link the input and output parameters. The single input/single output models in [11] were extended to multiple inputs/single output by the authors [13].

In the following sections, knowledge based fuzzy models are described together with the applied knowledge acquisition technique and the influence of the knowledge base. A short description of the utilized genetic algorithm, GAME, is given. This algorithm is applied to optimize structural components constructed from composite aluminum profiles with embedded continuous reinforcing elements. Finally the according results are discussed.

2. REPRESENTATIVE FORMAL DESIGN OPTIMIZATION PROBLEM STATEMENT

Such material and structural design optimization problems are nonlinear multi-criteria optimization problems of type

$$
\begin{array}{llll}
 & \text{„minimize“} & f_i(\{x\},\{y\}) & i=1,\,2,\ldots \\
(1) & \text{such that} & g_j(\{x\},\{y\}) & j=1,\,2,\ldots \\
 & \text{and} & s_k(\{x\},\{y\})=0 & k=1,\,2,\ldots
\end{array}
$$

where f_i and g_j are the objective functions (mass, displacement) and constraint functions e.g. on stresses, displacements, eigenfrequencies or acceleration levels, etc. The design variables $\{x\}$ may be continuous (i.e. geometry) or discrete (i.e. types of materials), and for given $\{x\}$ the response variables $\{y\}$ (displacements, stresses, ...) are to be determined from the system equations s_k. Depending on the type of problem, these system equations might be composed from those of structural mechanics (ranging e.g. from laminate plate theory to large finite element models) and e.g. cost models. As mentioned, especially in early development phases not every type of system equations might be fully available in time, which typically holds for manufacturing aspects. In order to assure the necessary completeness of the problem statement, approximate models based e.g. on response surfaces derived from qualitative knowledge should or even have to be included instead. This is described in the following.

3. KNOWLEDGE BASED APPROXIMATION MODELS

Different approximation techniques are well established for several engineering problems [5]. The most common are Response Surface Approximation (RSA), Kriging, and Neural Networks, which depend on large data sets to fit/train the model. Of these three methods, e.g. RSA offers a reasonable ability to consider both physical understanding and prior knowledge of the problem [14] in the building process of the approximation model. Examples can be found in [15]. This ability is useful to improve the quality of the approximation using a limited number of support points.

Fuzzy Rule Based Systems offer this ability by definition. They were originally developed by Zadeh [12] and many Fuzzy Logic based approximation techniques have been subsequently established such as Fuzzy Regression [16], Neuro-Fuzzy Systems, etc. [17]. The basic idea to use FRBS for expert knowledge representation in structural optimization was used by Hajela and Yoo in [11] to build a model for the layup time of a composite wing panel depending on one input parameter. For a detailed description of the 'if … then' rules refer to [13]. The rules are built by the knowledge engineer after the knowledge acquisition is performed.

3.1. Knowledge Acquisition

During the knowledge acquisition phase the input and output parameters of the model and their relations are identified and described by an expert or a group of experts. Afterwards this knowledge is transferred to a proper knowledge representation. An overview of different techniques can be found in [18]. It is important to distinguish between implicit and explicit knowledge. Implicit knowledge is general knowledge about a problem, whereas explicit knowledge contains rules and problem solving strategies. The approach for knowledge acquisition used in this paper is twofold: to gain implicit and explicit knowledge.

First Card or Concept Sorting techniques [19] are used to structure the expert´s knowledge. Previously defined objects, experiences, and rules are written on cards and the knowledge expert sorts them into groups. The expert describes what each group has in common so they can be hierarchically organized. This method is more efficient than the commonly used protocol analysis [19].

From the Card Sorting results, a structured interview [18] can be derived to develop the rule base of the FRBS by the knowledge engineer. Card sorting and the structured interviews can be easily supported by graphical user interfaces in, for example, Excel® or Matlab®.

As an example, different *events* were found for the extrusion process of composite aluminum profiles with embedded continuous reinforcing elements. They are listed in TAB 1.

Event	Effects on Structural Properties
residual stresses in profile after extrusion	$\sigma_{Allowed}$, suitability for subsequent manufacturing steps
debonding - loss of adhesion between fibers and base material	$\sigma_{Allowed}$, reject due to defects
deformation of profile cross section	cross section area, section modulus, tolerances
profile contour deviation due to gravity	overall geometry, tolerances
torsion of the profile	overall geometry, tolerances

TAB 1. Extrusion process events of reinforced aluminum profiles and effects on structural properties

3.2. Transfer of qualitative knowledge with fuzzy logic and fuzzy rule based systems

Fuzzy modeling is the most effective way to transform linguistic data into mathematical formulas. Fuzzy logic provides the basics for fuzzy modeling and it was introduced as a method of formally describing linguistic information [12]. So-called fuzzy rule-based systems (FRBS) soon showed their ability to model complex behavior. FRBS have four components: a fuzzification interface, a knowledge base, an inference engine and a defuzzification interface. The first component converts a real value into a fuzzy value; the last performs the inverse task with different methods. The inference engine we use is based on Mamdani's fuzzy inference method. The most important task is to build the knowledge base, which includes the *j* rules describing the relationship between inputs and outputs. The framework for the problem considered here is a system with *n* inputs $\{x_1,\dots,x_n\}$ and one output *y*. These rules *Rj* have the following structure:

(2) R_j: IF x_{j1} IS A_{j1} AND x_{j2} IS A_{j2} AND ...
AND x_{jn} IS A_{jn} THEN y_j IS B_j

with $x_{j1},\dots,x_{jn} \epsilon \{x_1,\dots,x_n\}$ and A_{ji} , B_j fuzzy sets on the respective domains of the variables. The degree an input or output belongs to a fuzzy set is defined by a membership value between zero and one. A membership function μ_A associated with a given fuzzy set maps a value to its appropriate membership value. Gaussian, triangle, trapezoidal and monotonically in-/decreasing membership functions are used (FIG 1). In fuzzy logic, a certain crisp value does not belong to one set or another set but can partly belong to different sets. For example, a profile with a length of 1250 mm would have a 0.5 degree of membership in the "short" set and a 0.5 degree of membership in the "medium long" set.

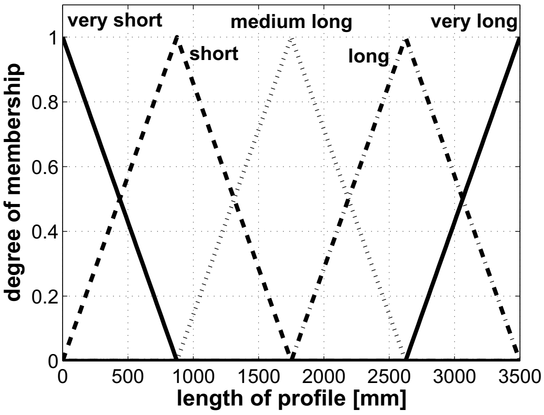


FIG 1. Membership functions for parameter “profile length”

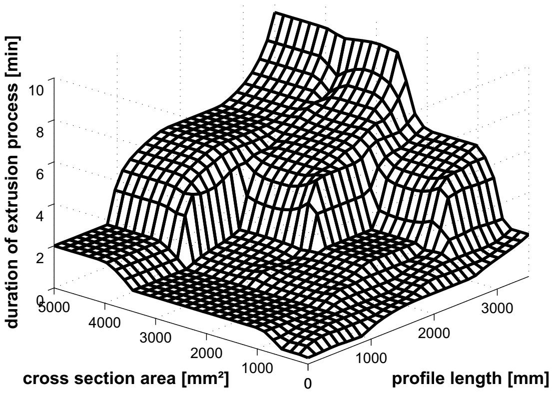


FIG 2. Output of fuzzy model “duration for “profile extrusion process”

The following steps are necessary to transform linguistic information into a mathematical model [20]. This is done together with the domain expert:

- Identify the input- and output variables and their respective domains
- Define the fuzzy membership functions for each input and output variable to cover the respective domains
- Transform the description of the system behavior into fuzzy rules stating the relations between the variables
- Evaluation of the model

The output of such a model is shown in FIG 2. Linear as well as non-linear characteristics can be achieved in a relatively simple way. These models are used to approximate manufacturing influences like geometric restrictions or manufacturing effort, which is described in the next section.

4. MANUFACTURING INFLUENCES ON STRUCTURAL DESIGN

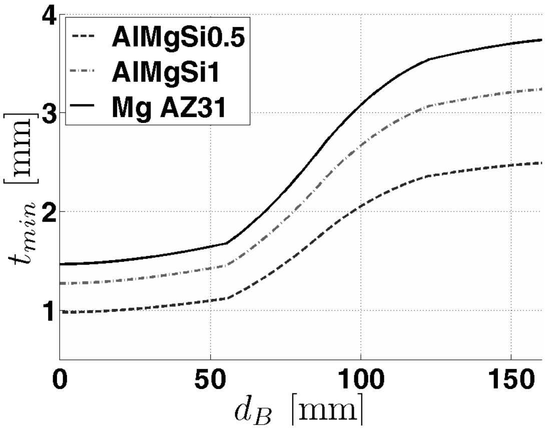
Beside the overall topology and configuration of a structure the manufacturing process of each part and each joining can have an influence on the structural properties, behavior and cost. Primary forming (e.g. casting, deep drawing, laminating) is followed by additional manufacturing processes (e.g. cutting, machining, heat treatment) and finally the single parts are placed and connected (screw joint, substance-to-substance bond, gluing, positive fit). Each step has its own optimal process settings, restricting the achievable geometries and sometimes changing the material properties. The process boundaries are especially critical for lightweight design and should be considered in the optimization task.

Cost has to be considered in every industrial application and the choices made in early product development stages are most important for the final cost of the product. Even estimations provide advantages in the evaluation of different designs. We introduce a manufacturing effort value based on simple cost estimations.

For many manufacturing steps process simulations are available ([21], [22]), but cannot be integrated practically in optimization (long computation time, not usefully parameterized). Approximations (e.g. neural networks, response surface approximation) based on simulation or tests [11] can reduce the computational effort if enough information is at hand. In addition, cost models for single processes as well as cost models for a whole production chain are available but are often very specialized and depend highly on existing data [23], [24], [25].

The use of extruded, hollow section profiles in space-frame construction offers a good potential for lightweight design. Aluminum and magnesium forging alloys allow the relatively cost effective production of thin walled cross sections, which are optimal adapted to the given loads. The low Young’s modulus and yield strength of these materials is nevertheless a disadvantage. To improve these properties of aluminum or magnesium profiles additional reinforcements are embedded, resulting in a metal matrix composite material (MMC). Particle or short fiber/particle Al-MMC’s (Al matrix + Al_2O_3 or Al matrix + SiC) unfortunately cause a high tool wear in all manufacturing steps and the material cost for the extrusion billet is high. Another way to produce reinforced profiles is to use standard billets (e.g. aluminum AA 6060) and to integrate the reinforcing elements during the forming process [26]. This is successfully managed for steel wires on a 10 MN extrusion press. Research for carbon fiber reinforcement is at laboratory level. The long fiber reinforced profiles are rounded directly after the extrusion mould [27] and therefore no following bending process is necessary to reach their final shape.

The profile is described by its three dimensional contour, its cross section and material. The minimum wall thicknesses of the cross section depend on different parameters. For aluminum alloys with higher strength and magnesium, the minimum value can double in comparison to AlMgSi0.5. The circumscribed diameter of the profile and the complexity of the cross section are the other main parameters (FIG 3).



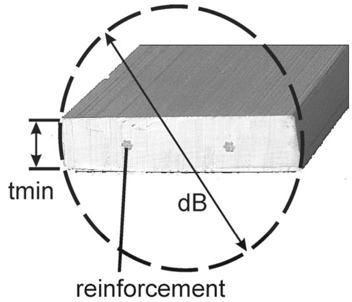


FIG 3. minimum wall thickness for complex aluminum and magnesium profiles as function of circumscribed diameter

In combination with reinforcing elements, the minimum wall thickness increases further in order to manage a process-sure embedding. The wires or ropes have at least a diameter of 1 mm and together with the minimum distance between two reinforcing elements, the maximum volume ration for a given cross section is determined. The three-dimensional contour of the profile is limited by the space available for rounding. For different profile lengths, the extrusion press and/or the cooling devices restrict rounding angles and radii.

Costs for one profile are affected by the material cost and the operating/labor cost depending on the time needed for extrusion molding (rounding is done simultaneously). This manufacturing time is basically related to the cross section, the profile length and the matrix material. The extrusion speed for aluminum is about twice the extrusion speed of magnesium. The operating cost of the rounding device can be neglected in comparison to the extrusion press, but the necessary guiding tool has to be considered. Such a guiding tool can cost up to one third of the extrusion die cost. Other considerations like acquisition and development cost are neglected in this paper.

The two manufacturing processes are investigated at the moment and the simulation tools and tests don't provide enough parametric information to model the above described influences. Only the domain expert can provide parametric interactions based on his experience, knowledge and prediction.

5. THE EVOLUTIONARY OPTIMIZATION ALGORITHM GAME

For handling of such problems different optimization algorithms as well as user program management tools have to be available. The mix of different types of models and constraints leads to weakly structured optimization problems where for example gradients for response quantities w.r.t. design variables are difficult to obtain. The required handling of such weakly structured problems with multiple objectives and discrete optimization parameters has lead to our evolutionary algorithm GAME (Genetic Algorithm for Multi-citeria Engineering).

The general flow chart of GAME is shown in figure 3. In addition to standard evolutionary algorithms (EA), GAME offers the following features:

- special adaption for multi-objective optimization
- treatment of continuous and discrete design parameters
- integration of response surface approximation (RSA) and math optimizers
- introduction of competing sub-populations with adaptive evolutionary operators
- high parallelization in the function evaluations for the ES and a SQP algorithm running in parallel and using RSA

These interesting features often more than compensate the high number of iterations needed compared to those of the stricter mathematical optimization algorithms. This algorithm is described in more detail in [28].

6. OPTIMIZATION OF REINFORCED STIFFENER PROFILES WITH MANUFACTURING CONSTRAINTS

For extruded, double-T section framework beams to be made out of aluminum or magnesium base material, additional reinforcement is introduced during the extrusion process in order to increase strength and stiffness of the profiles. So material, structural and manufacturing aspects have to be considered simultaneously for optimization [13]. The geometric relation between the global geometry, the material and the minimum wall thickness is modeled as shown in FIG 3. The minimum wall thickness for an extruded profile without reinforcements is a function of the circumscribed diameter d_B and the matrix material. Reinforcements increase the minimum wall thickness because the reinforcing elements have to be pulled by the matrix material during the extrusion process. The ratio between web and flange thickness and the number of reinforcing elements are input parameters for the manufacturing effort model for extrusion molding. The output of this model is a nondimensional effort value between zero (very low manufacturing effort) and one (high manufacturing effort).

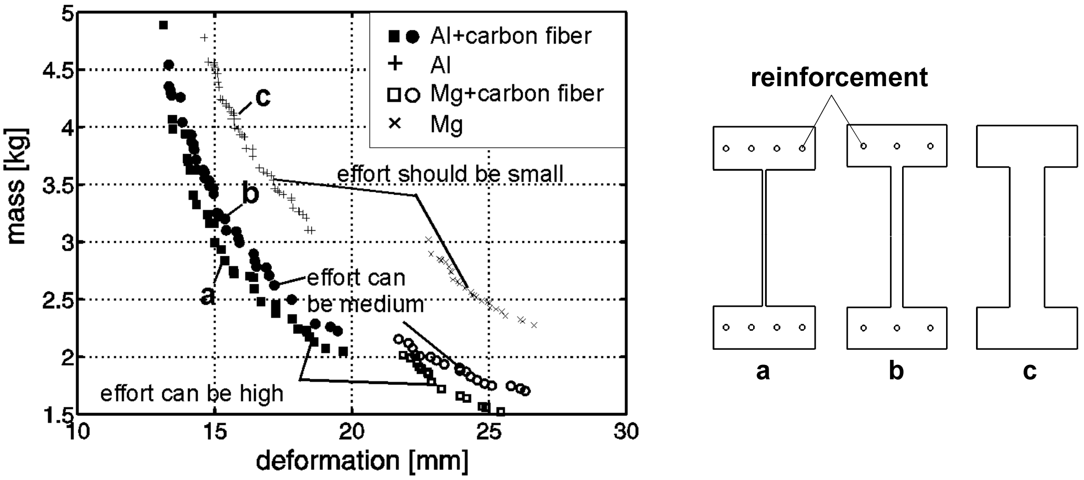


FIG 4. Optimization results for the double-T section beam: on the left side Pareto fronts for different manufacturing effort restrictions; resulting into different designs given on the right side

In FIG 4 three Pareto fronts (set of all optimal compromises between conflicting objectives) for different design optimization cases with varying constraints in manufacturing effort are shown. Each point is an optimal design, which means, that no design with a lower mass can be found for a given deformation. The 'ultimate' design would be placed at the lower left corner of the diagram. If high manufacturing effort is tolerated, aluminum profiles with carbon fiber reinforcements are optimal (material costs are neglected). Parts with less than 2 kg mass can be achieved with magnesium - carbon fiber combinations. Four to six reinforcing elements are located in the flanges and the web and flange thicknesses are quite different leading to lower mass but higher manufacturing cost.

7. SUMMARY AND OUTLOOK

Methods to implement qualitative knowledge into multi-objective optimization problems have been presented. With the help of knowledge acquisition techniques, fuzzy models are built for influences for which little or no simulation or test data is available. The method is demonstrated on the optimization of a profile.

The knowledge based models provide approximations which can be refined further during the development process. Nevertheless, further investigations are necessary to take possible uncertainties into account during the optimization process. This affects not only the approximation model itself, but also the optimization algorithm. The proposed method is a promising complement to other soft computing techniques utilized in early product development stage optimization.

A transfer of the approaches to fiber composite structures and their manufacturing aspects looks feasible and beneficial. For example, fiber placement and layer tapering are parameters interacting with design and manufacturing.

This paper is based on investigations of the collaborative research center SFB/TR10 which is kindly supported by the German Research Foundation (DFG).

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