How to harmonize design and production process in modern boatbulding

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ABSTRACT. The aim of the study is to provide an analytical tool to manage together design process and production methods in the construction of technologically advanced crafts made in composite materials.
The main objective is to introduce, in an medium size company, where even today decisions are often based just on experience of manufacturers and on empirical criteria, a new approach which could allow to quickly control and enhance products quality by minimizing at the same time production costs. The proposed approach is based on a objective comparison of different possible manufacture solutions.
To achieve this goal, it is necessary to combine a variety of different engineering subjects: technology and theory of composite materials, finite element based design methods, multi-attribute decision-making theory. The work here presented deals with the definition of a method for harmonizing design and production process, that combines all those engineering skills.
In the paper, after a brief introduction to the whole procedure, special attention is given to the setting of parameters for the multi-attribute approach. Procedure is discussed by making reference to a case study where extensive FE analyses have been carried out.

INTRODUCTION

In the following, an analytical tool which allows to manage together design and production methods in construction of technologically advanced craft in composite materials is discussed. The main target is to enhance products quality while restraining production costs and time. The proposed design and production approach suit needs of small to medium size boatyards oriented to high-technology products.
In applying such an approach, one has to proceed from a deep knowledge of the boatyard practice. Only on these basis it is possible to settle, for any given manufacture, practicable alternative solutions, each of them characterized by an array of objective attributes. That attributes, if well set, may allow to rank alternatives with respect to aggregated performances. Product alternatives and their characteristics have to be handled by mathematical methods provided by engineering. It is worth pointing out that a comprehensive procedure should consider all variables involved in the design and manufacture process.
The proposed procedure may be briefly summarized by the flowchart shown in Fig. 1, which gives a general idea of the steps and complexity of the process. Harmonization of design and production subjects as far as interconnection between different engineering and non-engineering aspects is clear from the figure.
As shown in Fig. 1, analysis of a project should be based on discussion of current design and production processes, where main product features are provided by the laminate plan, the systems layout and the interior layout. Such a discussion should involve specialists in all fields (structures, systems/plants and interiors) in order to clearly identify main issues of the project and to quickly come to sound shared options for the set of alternatives in accord to the principle of "concurrent engineering".

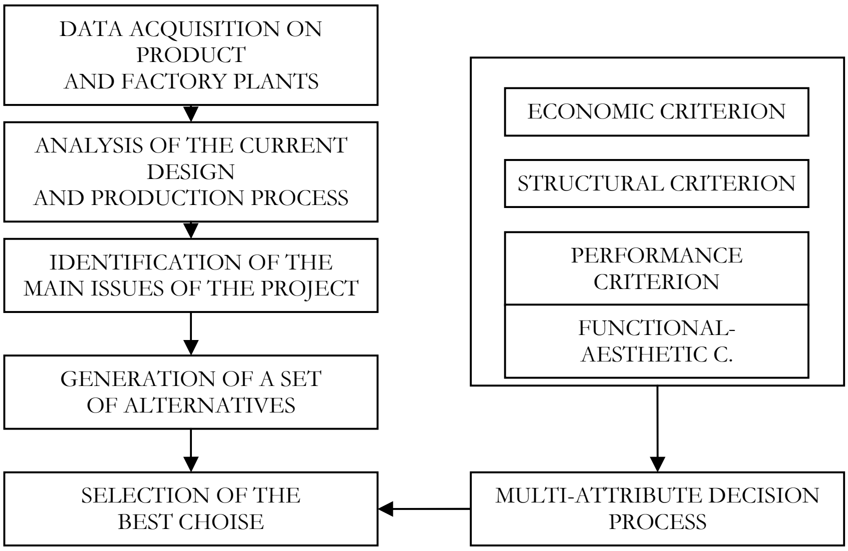

Figure 1: Operative procedure flow chart.

THE DECISION-MAKING PROCESS

The core of the proposed procedure is the multi-attribute selection technique set to provide the designer a method of objective classification of product's design and manufacture alternatives. Decision-making procedure is performed by the well tested TOPSIS method, where acronym stands for "Technique for Order Preference by Similarity to the Ideal Solution". It is based on idea that it is possible to get a ranking of options by measuring the "Euclidean distance" of each alternative from the optimal solution.

Each option may be characterized by a set of features laying in mutually independent criteria. The main evaluation criteria have been defined by authors in number of four: Economic Criterion, Structural Criterion, Performance Criterion and Functional-Aesthetic Criterion. The feature characteristics of each criterion is measured by a set of physical parameters which are fully comprehensive and are able to quantify by numbers each specific criterion. Such parameters are called attributes.

To properly apply a multi-attribute method, principles to assign relative weights to every attribute are to be considered carefully, as final choice is highly dependent on such weights, which may often be fixed just by an empirical approach. In what follows, nature and formulation of attributes for each selected evaluation criterion are discussed.

Economic Criterion – Economic performance of each alternative may be considered as quite defined through two parameters: cost C and time T of manufacturing. Such attributes are not completely independent but their proper combination gives a good comprehensive measure of features lying in the criterion. Approximation comes from disregarding costs of design process. The two attributes are given by:

$$C = \sum_{i=1}^{N_m} C_i = \sum_{i=1}^{N_m} A_i N_i \left[P_i + M_i \left(K_{L,i} + K_{D,i} \right) \right]$$

$$T = \sum_{i=1}^{N_m} T_i = \sum_{i=1}^{N_m} A_i N_i H_i \left(K_{L,i} + K_{D,i} \right)$$

where C_i is the manufacturing cost associated to the i-th material-location combination (of a total of N_m different cases), A_i is the area of laminate surface, N_i is the number of plies, P_i is the material cost per unit area, M_i is the manpower average cost per unit area and referred to the single ply, while $K_{L,i}$ and $K_{D,i}$ are coefficients which measure difficulty in plies laying down and laboriousness associated to patch complexity. A first attempt to define K-coefficients is the following: $K_{L,i}$ ranges from 1 to 5 under judgment of production manager (for instance, 1 - no difficulty, 2 - quite simple, 3 - average difficulty, 4 - difficult, 5 - quite difficult) and $K_{D,i}$ could be set equal to 0,7 + 0,3 N_i. In the T expression, H_i is the average time for laying down a unit area of ply. The average production costs should be based on statistics made by yard and on experience gained over time.

Structural Criterion – By this criterion, strength of composite materials used in boat building is evaluated in relation to standard limits by performing a series of FE analyses. Strength evaluations are based on two safety parameters: the Tsai-Wu failure index (in the following, *FI*) calculated on any ply and the actual to limit shear stress ratio, also called specific shear stress (in the following, *SS*), given for any core.
Strength performance of each structural element may be expressed by two attributes, the safety factor index (*SF*) and the strength balance index (*SB*) defined as following:

$$SF = \max\{FI, SS\}$$

$$SB = |FI - SS|$$

The safety factor index *SF* gives the lower safety level calculated by FE analyses on the laminate element. It represents closeness to composite collapse by independently taking into account collapse of any ply or core and considering that the two ways of breaking are equally dangerous. The strength balance index *SB* measures lack of balance between the two safety parameters of plies and core for a given laminate element. This parameter is very important as it allows to highlight any imbalance within the structure due to excessive strength of one of the two components of laminate. Both indexes range from 0 to 1. As for *SF*, the better performance depends on structural designer target, while the lower *SB* value, the more refined is the laminate structural design.
Performance Criterion – This criterion try to identify what is the alternative contribute to benefits in terms of boat speed, which in turn affects fuel consumption and stability. In the design of structural elements, it seems reasonable to consider as a performance index the weight *W* of each alternative, that may derived by FE analyses.
Functional-Aesthetic Criterion – With the last criterion we will assess what is the aesthetic impact of the alternative and its functionality in relation to comfort on board. This parameter gains or loses importance depending on how detailed analysis is, in relation to both appearance of the item under consideration and its functional performance. A first value for the attribute which combines all features of the criterion is a number ranging from 1 to 5. More detailed parameters may be used, as the stiffness of laminate panels and their aptitude not to be strained by loads.
Once attributes had been fixed or calculated, the relative weights of each attribute may be defined. For instance, in the study of structural strength of laminate elements, a possible set of values may be fixed depending on the target of boat designer: three possible different boat categories may be defined, that is Race, Economy or Cruise, being names self explicative.

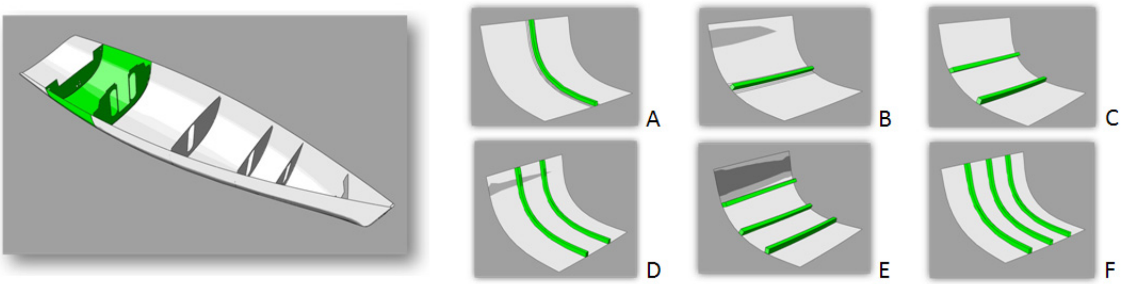

Figure 2: Hull structure portion and structural configuration alternatives.

THE CASE STUDY

The described procedure may be successfully applied to any problem of interaction between system/plants and structures or to strictly structural design. In what follows, the case of the structural design of a portion of the hull of a sailboat is discussed. More precisely, a section of hull between two transverse bulkheads has been studied which is very common in sailboats, in order to define the better structural configuration by modifying type and number of stiffness and type of laminate. Alternatives have been defined by authors by making reference to GL standards for strength requirements. Fig. 2 shows the part of the hull that has been studied together with the different alternatives taken into consideration as possible practicable options.
The more demanding phase in performing procedure is to carry out FE analyses for calculating attributes related to the structural criterion. Linear elastic FE analyses have been developed on fine-mesh shell elements models by making use of MSC Patran/Nastran software and MSC Laminate Modeler package for generation of sets of laminate's characteristics. In Fig. 3 results of FE analyses are shown for one of the alternatives: the shear stress distribution on the laminate core is

shown in the left hand picture, the worst Tsai-Wu failure index on each ply element is shown in the central picture, and finally displacements are given for the same structure in the right hand picture. The other attributes are calculated or fixed in accordance with above, and considering that the greater the number of stiffness, the higher will be the weight of the structure as long as cost and production time. Functional-Aesthetic Criterion has been disregarded.

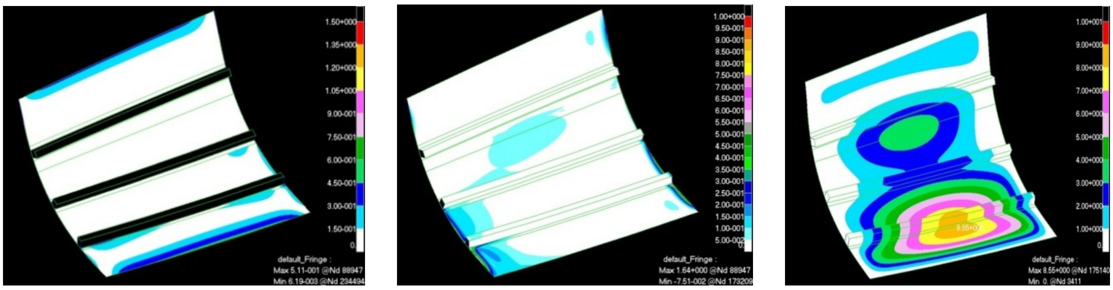

Figure 3: FEA results for the E-alternative.

In Fig. 4 both the performance matrix for the six alternatives and the relative weight matrix for three boat target are shown.

	C [€]	*T* [h]	*SF* [-]	*SB* [-]	*W* [N]
A	4085.00	55	0.33	0.11	940
B	4131.00	53	0.23	0.09	950
C	4739.00	92	0.70	0.38	730
D	4310.00	77	0.45	0.20	780
E	5873.00	128	0.95	0.60	770
F	5722.00	120	0.40	0.10	760

	C [€]	*T* [h]	*SF* [-]	*SB* [-]	*W* [N]	Sum
Race	0.05	0.00	0.05	0.10	0.80	1.00
Economy	0.40	0.20	0.30	0.05	0.05	1.00
Cruise	0.20	0.10	0.50	0.10	0.10	1.00

Figure 4: Performance matrix (above) and relative weight matrix (below).

By application of the TOPSIS multi-attribute selection technique, a ranking of the six alternatives has been generated. Fig. 5 shows a comparison among the six options: the center of tetrahedron identifies the worst solution, while along the edges between center end each vertex the ranking of alternatives is given for the three boat target with the best solution on the right vertex. Results are in good accordance with the boatyard expectances. Indications about relative performances of the different structural solutions are judged by boatyard as a good starting point for future structural design enhancements.

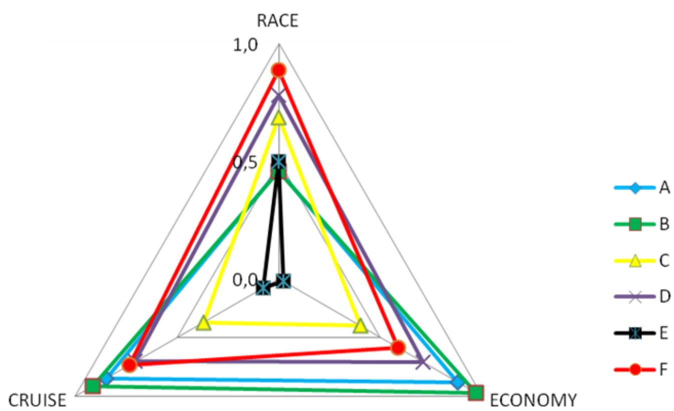

Figure 5: Final results for the case study.

CONCLUSION

A procedure has been defined to manage together design process and production methods in the construction of technologically advanced crafts made in composite materials. The proposed approach is based on a objective comparison of different possible manufacture solutions and on a multi-attribute criterion for supporting decision-making processes. In the paper, after a proper definition of evaluation criteria, attributes and relative weights was given, a case study has been discussed. Results prove accuracy of proposed method and validate it as a powerful tool for reliable predictions.

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