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On the effect of subjective, objective and combinative weighting in multiple criteria decision making: A case study on impact optimization of composites

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ABSTRACT

To date, no specific framework has been developed to guide composite structure designers to select the optimum fiber types and fabric weave patterns for a given application. This article aims to, first, investigate the effect of weighting methods in multiple criteria decision making (MCDM) and then arrive at a systematic framework for optimum weave pattern selection in fiber reinforced polymer (FRP) composites. Namely, via measured data from an industrial case study, the TOPSIS MCDM technique has been applied to choose the best candidate among different polypropylene/glass laminates. As an input to TOPSIS, different types of subjective and objective weighting methods were initially compared to assess the role of relative importance values (weights) of design criteria. These included the Entropy method, the modified digital logic (MDL) method, and the criteria importance through inter-criteria correlation (CRITIC) method. Next, two new subjective weighting methods, named 'Numeric Logic (NL)' and 'Adjustable Mean Bars (AMB)' methods, were introduced to give more practical and effective means to the decision makers during the weighting of criteria. In particular, compared to the MDL, the NL method increased the accuracy of assigned weights for an expert DM. On the other hand, the AMB provided a more interactive, visual approach through MCDM weighting process for less experienced DMs. Finally, a generalized combinative weighting framework is presented to show how different types of weightings may be combined to find more reliable rankings of alternatives. The combinative weighting could specifically accommodate different scenarios where a group of designers are involved and have different levels of experience, while given a large number of alternatives/criteria in highly nonlinear applications such as impact design of composite materials.

Abbreviations

AE	Absorbed Energy
AMB	Adjustable Mean Bars weights
CRITIC	Criteria Importance through Inter-criteria Correlation
CM	Combinative Weights
DM	Decision Maker
EVD	Exterior Visible Damage
EW	Equal Weights
FEA	Finite element analysis
ID	Interior Damage
RLFT	Relative Loss of Flexural Toughness due to impact
RLUFS	Relative Loss of Ultimate Flexural Strength due to impact
MCD	Maximum Central Deflection
MCDM	Multi-Criteria Decision Making
MDL	Modified Digital Logic method
NL	Numeric Logic weights
FT	Flexural Toughness (of healthy sample)
UFS	Ultimate Flexural Strength (of healthy sample)
PW	Plain Woven
PM	Project Manager
RF	Reaction Force
ROC	Rank Order Centroid weights
RR	Rank Reciprocal weights
RS	Rank Sum weights
TW	Twill Woven
UD	Unidirectional
UW	Unbalanced Woven
WPM	Weighted Product Model
XMT	X-ray Microtomography Technique

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Variables

A_i	Alternatives or materials ($i = 1, \ldots, m$)
$A*$	Positive-Ideal Solution
A^-	Negative-Ideal Solution
C_j	Criterion j or material properties ($j = 1, \ldots, n$)
C_i^*	Similarities to Positive-Ideal Solution
C_{jk}	Comparative Weight
r_{ij}	Normalized element of decision matrix
S_i^*	Separation from Positive-Ideal Solution
S_i^-	Separation from Negative-Ideal Solution
v_{ij}	Weighted normalized element of decision matrix
w_j	Weight or importance of criteria j
x_{ij}	Elements of decision matrix, ith alternative or material, jth criterion

Equations

1	Equal weights
2	Rank sum weights
3	Rank reciprocal weights
4	Rank order centroid weights
5	Adjustable mean bars weights
6	Modified digital and numeric logic weights
7–10	Entropy weighting method
11–12	CRITIC weighting method
13	Combinative weights
14	Modified combinative weights
15–19	Modified combinative weights for 3 scenarios
A1–A7	TOPSIS formulation

1. Introduction

Despite several advantages offered by fiber reinforced polymer (FRP) composites, such as low weight and yet high mechanical performance, their optimum use in specific applications including high-speed impact still requires development of new design methodologies, along with accurate numerical modeling and prediction tools (Alemi-Ardakani, Milani, Yannacopoulos, & Borazghi, 2015a). Currently, in order to avoid severe impact failures in composite structures, trial and error methods are most often employed by manufacturers through varying design parameters such as the composite lay-up and the shape of structures. In addition, most design decisions are made under *multiple*, often *conflicting* and *inter-dependent,* criteria. To exemplify this state of complexity in impact design of FRPs, the recent experimental case study (Alemi-Ardakani, Milani, Yannacopoulos, & Shokouhi, 2015b) suggested that the application of 'Multiple Criteria Decision Making' (MCDM) methods is paramount to select structures that can satisfy a multitude of design criteria at the same time.

Industrial practitioners and researchers frequently employ different MCDM and criteria weighting techniques through their design of expert systems. For example, Monghasemi, Nikoo, Khaksar Fasaee, and Adamowski (2015) used a multi-objective algorithm incorporating the NSGA-II (non-dominated sorting generic algorithm) during a highway construction project to find optimum design alternatives. In the weighting process, they used Shannon's entropy technique to weigh the conflicting criteria of time, cost and quality. In another research, Cobuloglu and Büyüktahtakın (2015) proposed a stochastic analytical hierarchy process (AHP) weighting method for MCDM in design of an expert system for sustainable biomass crop selection. Their selection matrix included 16 sub-criteria from three main sustainability criteria categories; namely economic, environmental and social categories. Yavuz, Oztaysi, Cevik, and Kahraman (2015) used a hierarchical hesitant fuzzy linguistic model to utilize the linguistic evaluation of multiple experts in selection of alternative-fuel vehicles. Different MCDM approaches such as ELECTRE, TOPSIS and the Grey Theory were studied and compared in the work by Özcan, Elebi, and Esnaf (2011), specifically for expert selection of warehouse locations. The results of TOPSIS and ELECTRE appeared to be similar, despite their very different calculation algorithms. However, given the high sensitivity of criteria weights in most design case studies similar to those above, it has not been shown how different 'subjective', 'objective' and 'combinative' criteria weighting methods in MCDM would differently capture the expertise of the same (given) designer, along with statistical characteristics of the measured data.

To address and exemplify the above effect, in the present work a set of common weighting methods from the literature (Modified Digital Logic, CRITIC, and Entropy methods) have been selected and tested against a same composite designer and the same data matrix from a FRP impact design case study. In addition, two new weighting methods, namely an adjustable mean bars (AMB) method and a modified digital logic (NL) method, have been introduced for the first time, along with a new generalized framework for combining different types of weighting methods, to accommodate different experience levels of decision makers. It is argued that the NL can increase the accuracy of weighting for an expert designer, while the AMB can provide a more intuitive direction through weighting process for a decision maker with potentially less experience/information, especially for complex design problems such as FRP impact where the underlying mechanical theories are still under development. For the selection/ranking stage of MCDM problem, among various techniques, the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) (Hwang & Yoon, 1981) has been employed owing to its popularity and efficiency. Examples of other common selection methods in the reported literature include Lexicographic (Paul Yoon & Hwang, 1995), Elimination by Aspect (Tversky, 1972), Simple Additive Weighting (SAW) (Fishburn, 1967), Weighted Product Method (Bridgman, 1922), ELECTRE (Roy, 1991), Median Ranking (Cook & Seiford, 1978), PROMETHEE (Vincke & Brans, 1985), and Analytic Hierarchy Process (AHP) (Saaty, 1980).

1.1. Case study description

The MCDM problem herein is based on the experimental data obtained by Alemi-Ardakani et al., 2015b via an industrial case study where the ultimate goal is to choose the most promising fiber reinforcement architecture for impact applications. Four thermoplastic composite candidates have been presented: plain woven (PW), twill woven (TW), unbalanced woven (UW), and unidirectional fiber tape (UD). Nine attributes (design criteria) were recommended including the reaction force during impact (RF), absorbed impact energy (AE), the maximum central deflection of the laminate (MCD), areal fraction of induced interior damage (ID), the exterior visible damage area (EVD), ultimate flexural strength of the healthy (non-impcated) sample (UFS), the relative loss of ultimate flexural strength due to impact (RLUFS), flexural toughness of healthy sample (FT), and the relative loss of flexural toughness due to impact (RLFT). Table 1 summarizes the matrix of experimental data obtained from drop tower impact testing, four-point flexural testing, and non-destructive damage evaluation (visual inspections and x-ray microtomography). For a general impact-resistant structure such as a roadside barrier (Fig. 1), the criteria AE, UFS and FT would be benefit-like (i.e., the higher the better), while RF, MCD, ID, EVD, RLUFS and RLFT would be cost-like (i.e., the lower the better). Table 2 shows the order of preference of candidate materials within each column (design attribute) of Table 1; i.e., one-factor-at-a-time (OFAT) optimization based on the objective related to each specific criterion. Notably, the order of preference of candidate materials is not identical between any two columns in Table 2, showing *the highest level of criteria conflicts,* hence the critical need for a robust weighted MCDM approach in composite impact optimization problems. Methodological considerations of the proposed methods are presented in Section 2, followed by the case study results and discussions in Section 3. Section 4 includes concluding remarks and potential future work.