Multi-criteria decision making/selection using weighted sum method and team-compromise instrument

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Abstract

Multi-criteria decision making based on values and preferences of the decision makers has been a major challenge in selecting the optimal material for any engineering product design. However, to evaluate the criteria weights by importance as a major valuable tools in decision making among the team members are another problem being faced in group decisions. In this paper weighted-sum method is adopted for solving material selection problems. The team-compromised approach is introduced as a parameter in the model by combining the subjective weights and objective weights of importance of the criteria in the decision making process. Two examples are presented to illustrate the efficacy of the model. The results shows that the proposed model is capable of selecting the best material taking into account the material selection criteria.

Keywords: Multi-criteria, Criteria preference, Material selection, Team-compromised, Decision-making

1.0 Introduction

Material selection is the bed rock of all engineering design and applications. This selection process can be described with respect to application requirements, possible materials, physical principles, and selection. The decision to select an alternative material among several available options is one of the challenges faced by designers. The selection process often involves several criteria that need to be enhanced effectively.

Product component material is regarded as one of the important parameters in the process of engineering product design. Charles (1989) has mentioned in his paper that in the materials selection plays an important role in the development of a product, as important as design and manufacturing and that all these activities are interrelated. The mechanical, physical, chemical, electrical, magnetic property requirements solely depend on the selected materials. Others which partly depend on component materials are product manufacturability; rigidity and stability of overall structure; safety, cost, and functionality. Consequently, material selection process appears to be one of the critical factors among the tasks that have to be accomplished in engineering design. Material selection is one of the most important activities for a product development process. In the modern design manufacturing environment such as newly-developed concurrent engineering methodology, material selection plays an important role in other activities in the total design model such as market investigation, product design specification, component design, design analysis, manufacture and assembly as shown in Figure 1. The total design model stated that in any product development, there are some steps to be carried out such as market investigation, product design specification, conceptual design, detail design, manufacture and sale (Pugh, 1991; Sapuan, 2001). Materials selection is the process of choosing the best material for a particular design; in mechanical design, materials selection enters at every stage of the total design process.

Material selection methods have been in development for more than ten years. These methods typically aim to select the most appropriate solution for a given application (Haihong et al. 2010). However, the importance of decision making/selection in design has increased in recent years due to the range of approaches available to the engineers is much larger than ever before. This represents the opportunity for innovation in design by utilizing these materials in products that provide greater performance at lower cost. To achieve this, it requires a more rational process for materials selection in deciding an appropriate optimization method that will help the decision maker to make the best choice of material for the product design.

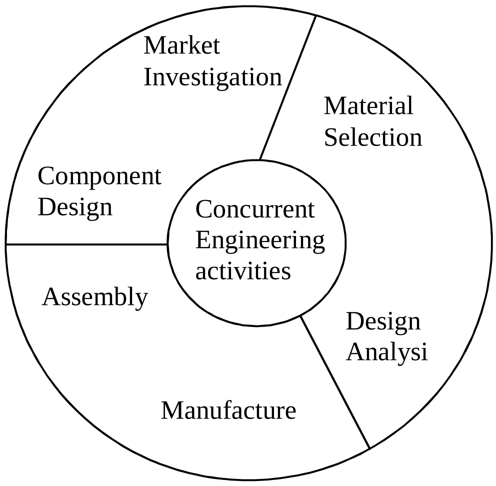

Fig.1 Material selection in production development

Source: Sapuan, 2001

Gutteridge and Water-man (1986) described the aim of materials selection as the identification of materials, and with appropriate manufacturing operations, and with the right dimensions, shape and properties necessary for the product or component to demonstrate its required function at the lowest cost. Selecting the best material for a particular component involves more than selecting a material that has properties to provide the necessary performance in service; it is also connected with the processing of the material into the finished part. A poorly chosen material can contribute to the manufacturing cost of a part and increase its price. Also, the properties of the material can be changed by processing (beneficially or detrimentally), and that may affect the service performance of the component.

To choose the appropriate material for a specific process, the designer should be familiar with a lot of materials to avoid confinement of some particular materials. The designer also utilizes new materials and processes to enable innovation in design. The engineer improves product performance and eliminates material or service failure. Moreover, the designer solves processing difficulties and takes advantage of new processing techniques, reduces material and production costs, and anticipates or exploits a change in the availability of material.

The choice of a material is frequently the result of several compromises. For example, the technical appraisal of an alloy will generally be a compromise between corrosion resistance and several other properties such as strength and weldability. The objective of any material selection procedure is to identify appropriate selection criteria or material properties that may be associated with the design product or component. It is a known fact that the performance of an engineering component is limited by the properties of the material for which it is made, and by the shapes to which this material can be formed. Thus, an attempt to identify these criteria that influences material selection for a given engineering design need to be considered so as to eliminate unsuitable alternative, and to select the most suitable alternative using simple and logical methods such as multi-criteria methods (Rao and Patel 2012).

2. Multi-Criteria Decision-making

In the Multi-criteria material selection problem, design situations exist where all these criteria may have to be satisfied simultaneously. Methods of solving the single criteria version have been in existence. They are based mostly on experience; searching Engineering Handbooks and Material Databases as well as the use of Artificial Intelligence (Ermolaeva et al. 2002, Roth et al. 1994). Unfortunately, these approaches are grossly inadequate for handling the multi-criteria version for obvious reasons (Savic 2002; Wu et al. 2010). A solution based on a single criterion may provide worst solution value for other criteria. For instance, the selection of material with minimum density may not provide for the desired toughness and insulation; another with maximum electrical conductivity may not provide for the ultimate strength and cost requirements. In one design situation, several combinations of these opposed requirements which render one-criterion solution approach unsuitable may arise.

The use of multi-criteria decision-making in material selection evaluation enable decision maker to express his/her point of view without fear and intimidation in decision making process. Though, selecting non-arbitrary weights can be very inefficient and awkward. Thus, responsible for decision makers to assign different weight values on each criterion. This leads to conflicts and make weights determination time consuming and costly. The main objective of this paper is to present a decision-making method that can select an appropriate material for any engineering. And for the purpose of this proposed method and some decision-making approaches, criteria weights determination is an important factor that influences the selection process, as alternatives are selected based on the criteria weights and several criteria under consideration. So, for this study, criteria weights based on team-compromised approach will be adopted.

The criteria weights determination could be classified into two aspects namely: objective and subjective approach. In the case of objective approach, criteria weights determination is evaluated by means of mathematical models from information provided in each criterion (Aldian and Taylor, 2005). While in the case of subjective approach, criteria weights is determined based on the subjective judgment of the decision maker acting independently. It is usually causes conflicts between decision makers as a result of their differences in judging the problem under consideration. In this case, criteria weights are computed using a compromised weighting method in order to take into account the subjective and objective weights approaches.

Notice that there are two conflict situations likely to arise from applying the single criterion approach to solving the Multi-criteria material selection problem. Both problems may be resolved only by constructing a model which can rationally forge acceptable compromises to ameliorate these criteria-based conflicts with well-informed individuals' preferences taken only as model inputs. The adoption of weighted-sum method for multiple criteria material selection using team-compromise instrument as a means of defining the criteria weights associated with the product design is the main thrust of this study.

Most real-life decision-making problems are multi-objective by nature, this means that decisions are made according to multiple and conflicting criteria, conflict arising from the design team in making choices, such that each member of the team of designers may have a preference for some criteria. For instance, using the principle of design for assembly, design for manufacture, design for safety, design for cost and so forth, where everybody wants its point of view. The mechanical engineer, for instance, may prefer mechanical properties for certain product/component are not compromised; Electrical engineer, electrical properties; Safety Engineer, safety-related properties; Manufacturing engineer, manufacturing requirements; Cost engineer, cost requirements; even the Customer is interested in one property or the other, etc. Consequently, there is no unique optimal solution but rather a set of incomparable alternatives being compromised. In concurrent engineering environment, team of designers works together, and sometimes, whenever this group of people comes together because of the passion for design in a team approach, wants his/her input to be heard, as such, there is always a conflict arising in specifying which material property or criteria is more important in the decision process. To eliminate these conflicts, thus the introduction of the team-compromised instrument, an approach that depends on the values and judgments of individuals and groups such that consensus is reached.

3. Formulation of the Weighted-sum Method

The weighted-sum method involves selecting scalar weights w_k and optimizing an objective function with non-negative weightings ($w_k \geq 0, k = 1, n$). The weighting method consists of solving a sequence of scalar problems where the objective is defined by a linear combination of all objective functions (Zhang and Yang 2001).

Let f_j be the objective function expressing the behaviour of material property j with respect to some known quantities. For a particular material selection situation, j = 1, 2, 3, . . ., N representing n different types of mechanical, electrical, chemical, thermal, economic, manufacturing, magnetic, etc. properties. In order to select materials which simultaneously combine the best of the requirements of each property, let F_i be an expression for a performance index combining the set of *n* objective functions into a single function as follows:

$$F_i = \beta_1 f_1(x_{i1}) + \beta_2 f_2(x_{i2}) + \ldots + \beta_j f_j(x_{ij}) + \ldots + \beta_n f_n(x_{in}) \qquad (1)$$

where

$\{\beta_j \,/\, j = 1,2,3,\ldots,n\}$; set of normalizing factors which allows dimensional consistency in expression (1).

x_{ij} : the value of material *i* for property *j*

Usually, one normalizes measurements so as to present relative deviation between

0 and 1. Normalization aims at transferring dimension into dimensionless quantity by providing a considerable format for combining set of objective functions into s single entity. Normally, in multi-criteria optimization problems, there are two major normalization functions. These include linear normalization and vector normalization.

In the case of linear normalization, the maximum value of a certain criterion j is defined, such that the normalized value p_{ij} for beneficial criteria and non-beneficial criteria (cost attribute) are evaluated.

For beneficial criteria (maximum value more preferable)

$$p_{ij}{}^{b} = \frac{x_{ij}}{x_{j}{}^{\max}} \quad (2)$$

For non-beneficial criteria (cost attribute) (minimum value more preferable)

$$p_{ij}{}^{c} = 1 - \frac{x_{ij}}{x_{j}{}^{\max}} \quad (3)$$

Where $x_j{}^{\max}$ is the maximum value of criterion *j*

$p_{ij}{}^{b}$ is the values of the beneficial criterion of alternative *i*

$p_{ij}{}^{c}$ is the values of the non-beneficial criterion of alternative *i*

And $0 \le p_{ij}{}^{b} \le 1$; $0 \le p_{ij}{}^{c} \le 1$

However, equation (2) and (3) can be modified such that the normalized value p_{ij} can be defined as:

For beneficial criteria

$$p_{ij}{}^{b} = \frac{x_{ij} - x_{j}{}^{\min}}{x_{j}{}^{\max} - x_{j}{}^{\min}} \quad (4)$$

For non-beneficial criteria

$$p_{ij}{}^{c} = \frac{x_{j}{}^{\max} - x_{ij}}{x_{j}{}^{\max} - x_{j}{}^{\min}} \quad (5)$$

The scale of measurement of equation (3) and (4) varies precisely from 0 to 1 for each criteria. Thus, if $p_{ij} = 0$, it represents the worst outcome of a certain criterion; and if $p_{ij} = 1$, it represents the best outcome of criteria j.

In the case of the vector normalization, the value of each criterion is divided by its norm such that the normalized value p_{ij} is expressed as:

$$p_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}{}^{2}}} \quad (6)$$

Where n is the total number of criteria and p_{ij} is the normalized value

Normally, using the weighted sum method to solve a multi-criteria optimisation problem entails selecting scalar weights w_j and in this case, vector normalization function is adopted and the criteria weights is will be determined using the team-compromise instrument approach (see equation (6)).

Therefore, the normalization factor $\{\beta_j / j = 1,2,3,\ldots,n\}$ is defined as:

$$\beta_j = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}; \qquad i = 1, 2, \ldots, m; \quad j = 1, 2, 3, \ldots, n \tag{7}$$

where x_{ij} is the value of material *i* for property *j*

Thus, the set of n objective functions in equation (2) becomes:

$$F_i(x) = \sum_{j=1}^{n} \beta_j f_j(x_{ij}); \quad i = 1, 2, \ldots, m; \; j = 1, 2, \ldots, n \tag{8}$$

Then substitute equation (7) into (8), and introduce criteria weight w_j , we have

$$F_i(x) = \sum_{j=1}^{n} w_j \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{9}$$

Hence, the weighted-sum problem can be solved by optimising the following functions:

$$\text{Max } F_i(x) = \sum_{j=1}^{n} w_j \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{10}$$

Subject to: $L_{ij} \le f_j(x_{ij}) \le U_{ij}$

Where L_{ij} : lower limit value of material i for property j

U_{ij} : upper limit value of material i for property j

But w_j is the weight assigned to criteria j by adopting team-compromised instrument. The team-compromised instrument is a team approach to design whereby different professionals and experts in design in a team agreeing on contentious design issues to compute consensus values for a set of criteria weights that is devoid of conflicts among the team members Odu and Charles-Owaba (2017) and can be summarized as follows:

The team member *i* to criterion *j* ranked the criteria and is denoted as ψ_{kj} and the associated score, R_{kj} is computed given by the following expression:

$$R_{kj} = N - \psi_{kj} + 1 \tag{11}$$

Where N is the maximum possible score on any criterion and 1represent the minimum by an individual. Then using ordinal ranking taking 1st, 2nd, 3rd, 4th, etc., without ties expression (11) signifies that the higher the rank, the higher the score. Let assume that Z be the team size. Since every member has to rank every criterion using the rank indicator (ψ_{kj}) without ties, the total score of criterion j (TC_j) by all Z members of the team is given by the expression:

$$TC_j = \sum_{k=1}^{Z} R_{kj} \quad (12)$$

The team preference index of criterion j, w_j, will be a function of TC_j which bring about the desirable properties of w_j, and can be expressed as:

$$w_j = \frac{TC_j}{\sum_{k=1}^{Z}\sum_{j=1}^{n} R_{kj}} = \frac{\sum_{k=1}^{Z} R_{kj}}{\sum_{k=1}^{Z}\sum_{j=1}^{n} R_{kj}} \quad (13)$$

where

$$\sum_{k=1}^{Z}\sum_{j=1}^{N} R_{kj} = \text{ZN(N+1)/2} \quad (14)$$

Equation (9) can be re-written by substituting (10),

$$w_j = \frac{\sum_{k=1}^{Z} R_{kj}}{\text{ZN(N+1)/2}} \quad (15)$$

In terms of the ranking variable (ψ_{kj}) in expression (11),

$$w_j = \frac{\sum_{k=1}^{Z} (\text{N} - \psi_{\text{kj}} + 1)}{\text{ZN(N+1)/2}} \quad (16)$$

3.1 Solution Procedure for Solving the Weighted-sum method

To solve the weighted-sum problem, the following steps needs to be followed:

STEP 1: Normalize the objectives. For w_j to reflect the relative importance of the criteria functions, all functions must have the same unit length of vector, facilitating inter-attribute comparisons, it is necessary to normalize the objectives, in order to convert all objectives into the same dimensions or dimensionless before combining it into one, so that all the functions can be uniform as a result of different dimension/units being transformed into dimensionless quantities. Also the values of different functions or the coefficients of the terms in the functions may have different order of magnitude.

STEP 2: Convert the minimizing objective, $f_j(x_{ij})$ to maximizing objective by multiplying it by minus one.

STEP 3: Aggregate the objective functions into a single function as shown in equation (10)

STEP 4: Solve the resulting model using the appropriate software or algorithm.

STEP 5: Rank the alternative materials.

4. Numerical Example

This section looks at two examples material selection of a given engineering applications used to validate the proposed approach and find the most appropriate material. These two examples are: (i) Material selection for Bicycle frame and (ii) Material selection for cell phones cases. Designers or the team members needs information guiding the properties/criteria ranking process in order to examine the product/components descriptions in terms of the functions, and other relevant properties and then apply their wealth of experience and technical know-how to rank each criterion. With the information provided, each team member should able to state the relative rank of each criterion in terms of their importance as either 1st or 2nd, 3rd, 4th, etc., reflecting their most preferred, second important, third important, fourth most important, without allowing ties between any pair of criteria. The ranks are then converted to scores using the model (team-compromised instrument) such that the criterion with the highest rank receives highest possible score, say N; second position criterion scores N-1; third position, N-2; fourth position, N-3; etc. Note that the criterion which receives high or low score depends on the judgment of the individual.

Example 1: Bicycle Frame materials

Bicycle frame is the most important component of a bicycle design. The design of an upright bicycle depends on the safety and the material used in the frame. Possible materials are screened and are limited to four categories; these are steel, aluminium, titanium alloy (ASTM grade1), and carbon fibre. The performance criteria for bicycle frame have broad range of mechanical properties including the manufacturability and cost requirements as shown in Table 1. As mentioned earlier, there is need to give detail information regarding the description of the Bicycle frame materials

These materials mentioned above have different characteristics with their advantages and limitations in terms of bike frame design as described below:

(v) Steel: Steel materials are known for high quality in strength with good durability and strong impact resistant. They are relatively easy and cheap to repair when damaged. Though the materials and manufacturing cost of steel bike frame are somehow low, but has some limitations that may hinder its selection such as heaviest metal among the four materials for consideration, also has the tendency to rust and may need occasional re-sprays from time to time. Moreover, the bike frame is made of steel tubing that is round and therefore has no aero profiling.

(vi) Aluminium which is regarded as a super light-weight with excellent power transfer. It is a tough material and fairly cheap manufacturing costs as compared to others. One of the disadvantages of aluminium made of bike frame is the fact that the material weaken over time, another is that it is hard to repair and can corrode easily when exposed to the atmosphere.

(vii) Titanium is another possible material that can be used for bike frame design, it has a very high strength to weight ratio and they are rustproof. It is found to compete with steel in terms of ride quality and resistance to metal fatigue. However, titanium materials are hard to repair and have high cost of materials. And due to its light weight frames, more powerful riders might find it too flexible making it to wobbles when descending with high speed.

(viii) Carbon fibre which is known to have high strength to weight ratio giving rise to the lightest bike frame available. It can be moulded into any shape with excellent resistance to fatigue and corrosion resistant, making aerodynamic design possible. Some of the limitations of bike frame made with carbon fibre have to do with high cost of raw materials, difficulty to repair if damaged, and tendency to break suddenly without prior warning especially when weakened.

Table 1: Material property for Bicycle frame

	Criteria/Property						
Alternative Material	Density (Kg/m^3)	Tensile yield strength (MPa)	Elongation (%)	Young's Modulus (GPa)	Thermal conductivity (w/m/K)	Melting point (^0C)	Cost ($/kg)
Aluminium 6061-T6	2700	276	12	68.9	167	588	2
AISI 1006 Steel	7872	340	20	210	65.2	1315	0.5
Titanium Alloy ASTM grade 1	4510	310	24	105	16	1670	15
Carbon fibre	1800	2537	2.5	230	165	3652	18

Table 2: Material Criteria type and criteria weight for Bicycle frame

Criteria	**Criteria type**	**Criteria weight (%)**
Density (Kg/m^3)	Non-beneficial	**19.29**
Tensile yield strength (MPa)	Beneficial	**23.57**
Elongation (%)	Beneficial	**13.75**
Young's Modulus (GPa)	Beneficial	**12.14**
Thermal conductivity (w/m/K	Beneficial	**14.29**
Melting point (^0C)	Non-beneficial	**6.25**
Cost ($/kg)	Non-beneficial	**10.71**

Using equation (11), the criteria weights is determined with the tensile yield strength as the most important criteria for the Bicycle frame design having the highest weight of 24 percent as shown in Table 2, followed by the density with 19 percent.

The rankings of alternatives materials for the bicycle frame were evaluated based on the team-compromised instrument in finding consensus weights for the criteria. The performance index value, $F_i(x)$ are computed for different materials or alternatives using equation (10) by optimizing the objective function. In this case, the objective function in equation (10) is maximized. This shows that for non-beneficial criteria/attributes that need to be minimized (the smaller value more preferable) will be converted to maximizing objective by multiplying it by minus one. The computed values of the performance index and ranks are given in Table 3.

Table 3: Performance index of the bicycle frame materials

Material	Performance index	Rank
Aluminium 6061-T6	0.8500	1st
AISI 1006 Steel	0.4729	3rd
Titanium Alloy ASTM grade 1	0.2844	4th
Carbon fibre	0.6054	2nd

From the results given in Table 3, it clearly shows that the usage of subjective weights and objective weights by adopting team-compromised instrument has leads to material ranking of Aluminium 6061-T6 as the first choice for the bicycle frame with the highest index value of 0.85.

Example 2: Material selection for cell phone cases

Cell phone cases provide the necessary protection which helps in preserving the phones appearance while minimizing the wear and tear. There are a variety of materials used for cell phone cases; these are metal, wood, plastic, leather, carbon fiber and silicone. For most users, the choice of material is largely influenced by factors such as: appearance, environment, customization, ease of use, budget, and protection from impact and scratches. Using qualitative analysis on the cell phones cases criteria to seek precise measurement in numerical form such as 5 for excellent; 4 for very good; 3 for good; 2 for fair; 1 for poor and 0.5 for very poor as shown in Table 2 with the following information on the phone case materials:

(vii) Plastic cell phone cases: The plastic cell phone case materials are classified into two major types: polyurethane and polycarbonate. They are known to be inexpensive cell phone cases material that comes in either soft or hard form. The Plastic cell phones material can be customized into many designs and pattern, easy to recycle and molded into desired shape. It also offers good protection and easy to holds or slide into a pulse or pocket. However, plastic cell phone cases has cheap look and requires cushion material for sufficient protection.

(viii) Carbon fibre cell phone cases: The carbon fibre is expensive material by weaving together strands of carbon that is even stronger than steel. Though carbon fibre is known to have attractive appearance and good protection against impacts of light weight but has a limited pattern and colours.

(ix) Wood cell phone cases: The wooden cell phones case material is easy to customized and engrave to unique designs. Typical woods mostly used are bamboo trees, redwood, and cherry, etc. However, the cell phones cases from wood are easy to hold, unique and attractive but expensive to make and not readily available in stock. It also has limited protection against great impact and falls.

(x) Metal cell phone cases: The metal cell phone cases tends to be heavier than the other materials, however, the metal case offer the best protection and can withstands impact whenever it drops. In addition, it has a distinctive look but sometimes difficult to hold because it is slippery. It is expensive compared to other materials and reflects radio waves which weaken the phone signal.

(xi) Leather cell phone cases: This type phone cases comes in form of natural and synthetic leather materials. Though, the natural leather is more durable and superior in quality than the synthetic leather material. The leather phone cases are stylish in nature with quality feel but no much protection against falls or heavier impacts. They are waterproof, long-lasting but rather too expensive to get.

(xii) Silicone cell phone cases: The silicone material is made from silicon and petroleum products. The cell phone cases are flexible and capable of absorbing the shocks during low-impacts drops making it difficult to break. The phone case texture is less slippery and easy to handle. It is durable and inexpensive, however, it comes in only one colour and not stylish compared to other materials.

Table 3: Material property data for cell phone cases

	Criteria that may influenced cell phone cases					
Alternatives	Protection from impact and scratches	Appearance	Customization	Environment	Cost	Ease of use
Plastic cell phone cases	4	1	5	5	5	5
Carbon fibre cell phone cases	5	5	2	3	1	4
Wood cell phone cases	3	5	5	3	5	5
Leather cell phone cases	2	5	4	5	2	4
Metal cell phone cases	5	5	4	3	2	3
Silicone cell phone cases	4	3	3	4	5	5

Table 4: Material Criteria type and criteria weight for cell phone cases

Criteria	**Criteria type**	**Criteria weight (%)**
Protection from impact and scratches	Beneficial	20.71
Appearance	Beneficial	21.19
Customization	Beneficial	9.29
Environment	Beneficial	15.48
Cost	Non-beneficial	9.76
Ease of use	Beneficial	23.57

Table 5: Performance index of the cell phone cases materials

Material	Performance index	Rank
Plastic cell phone cases	1.4559	5th
Carbon fibre cell phone cases	1.7685	2nd
Wood cell phone cases	1.5273	4th
Leather cell phone cases	1.7640	3rd
Metal cell phone cases	1.7715	1st
Silicone cell phone cases	1.3377	6th

From the results shown in Table 5, it can be seen that cell phone cases made of metal is selected as the best choice having the highest performance index value of 1.7715. The second and third preferred option is carbon fibre and leather cell phone cases with index value of 1.7685 and 1.7640 respectively. This result agrees with the analysis carried out by the team-compromised instrument for determining the criteria weights in Table 4, which indicates that the ease of use of the phone as the most preferred criteria having the highest weight value of approximately 24 percent of the total weights, followed by appearance and protection from impact and scratches with weights value of 21.19 and 20.7 percent respectively. This goes to show that from the above description of metal cell phone cases given earlier, that metal cell phone cases has strong affinity for the phone usage in terms of handling and durability, excellent appearance and has the best protection against impact and scratches.

5. Conclusion

The proposed method for material selection in this paper has been shown to be appropriate tool with the team-compromise approach such that it will help the decision maker to arrive at a decision based on both the subjective weights (individual team preference) and objective weights (mathematical model) of importance of the criteria. In addition, the methodology developed in this paper can simultaneously consider any number of quantitative and qualitative selection criteria as shown in numerical examples provided and this in turn will helps to obtain the performance index in evaluating and ranking the alternatives materials for any given engineering or other selection problem.

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Appendix A

Criteria ranking using ordinal scale for 20 team members (e.g., 1st, 2nd, 3rd, 4th, etc) for Bicycle frame materials

	Criteria						
Team members	Density	Tensile yield strength	Elongation	Young modulus	Thermal conductivity	Melting point	Cost
K1	3rd	1st	4th	5th	2nd	6th	7th
K2	1st	2nd	6th	5th	7th	3rd	4th
K3	2nd	3rd	4th	1st	6th	5th	7th
K4	2nd	1st	5th	4th	3rd	7th	6th
K5	1st	2nd	6th	3rd	4th	7th	5th
K6	3rd	1st	2nd	4th	5th	6th	7th
K7	4th	1st	5th	2nd	3rd	7th	6th
K8	3rd	2nd	4th	6th	5th	7th	1st
K9	4th	1st	6th	5th	2nd	7th	3rd
K10	2nd	1st	3rd	7th	4th	6th	5th
K11	3rd	2nd	1st	7th	6th	5th	4th
K12	4th	1st	2nd	5th	3rd	6th	7th
K13	3rd	1st	5th	6th	4th	7th	2nd
K14	3rd	1st	5th	6th	4th	7th	2nd
K15	2nd	1st	5th	4th	3rd	7th	6th
K16	1st	2nd	6th	3rd	4th	7th	5th
K17	3rd	1st	5th	2nd	4th	7th	6th
K18	3rd	2nd	1st	7th	6th	5th	4th
K19	3rd	1st	4th	5th	2nd	6th	7th
K20	2nd	1st	4th	5th	3rd	7th	6th

Appendix B

Criteria ranking converted to relative score (highest rank receives highest possible score) Bicycle frame materials

Team members	Density	Tensile yield strength	Elongation	Young modulus	Thermal conductivity	Melting point	Cost
K1	5	7	4	3	6	2	1
K2	7	6	2	3	1	5	4
K3	6	5	4	7	2	3	1
K4	6	7	3	4	5	1	2
K5	7	6	2	5	4	1	3
K6	5	7	6	4	3	2	1
K7	4	7	3	6	5	1	2
K8	5	6	4	2	3	1	7
K9	4	7	2	3	6	1	5
K10	6	7	5	1	4	2	3
K11	5	6	7	1	2	3	4
K12	4	7	6	3	5	2	1
K13	5	7	3	2	4	1	6
K14	5	7	3	2	4	1	6
K15	6	7	3	4	5	1	2
K16	7	6	2	5	4	1	3
K17	5	7	3	6	4	1	2
K18	5	6	7	1	2	3	4
K19	5	7	4	3	6	2	1
K20	6	7	4	3	5	1	2
	108	132	77	68	80	35	60
	0.19286	0.23571	0.13750	0.12143	0.14286	0.06250	0.10714
% weight	**19.29**	**23.57**	**13.75**	**12.14**	**14.29**	**6.25**	**10.71**

Appendix C
Criteria ranking using ordinal scale for 20 team members (e.g., 1st, 2nd, 3rd, 4th, etc) for Cell phone cases materials

Team members	Protection from impact and scratches	Appearance	Customization	Environment	Cost	Ease of use
K1	4	2	5	6	3	1
K2	2	3	5	4	6	1
K3	4	2	5	3	6	1
K4	1	3	5	2	6	4
K5	4	3	6	2	5	1
K6	3	2	6	4	5	1
K7	4	1	5	3	6	2
K8	6	3	5	4	1	2
K9	1	3	6	4	5	2
K10	1	3	4	6	5	2
K11	4	3	6	1	5	2
K12	1	2	5	4	6	3
K13	2	3	6	4	5	1
K14	1	5	2	6	3	4
K15	4	3	5	1	6	2
K16	1	2	5	4	6	3
K17	3	1	4	5	6	2
K18	4	2	5	3	6	1
K19	2	1	5	4	6	3
K20	1	4	6	5	2	3

Appendix D

Criteria ranking converted to relative score (highest rank receives highest possible score) phone cases materials.

Team members	Protection from impact and scratches	Appearance	Customization	Environment	Cost	Ease of use
K1	3	5	2	1	4	6
K2	5	4	2	3	1	6
K3	3	5	2	4	1	6
K4	6	4	2	5	1	3
K5	3	4	1	5	2	6
K6	4	5	1	3	2	6
K7	3	6	2	4	1	5
K8	1	4	2	3	6	5
K9	6	4	1	3	2	5
K10	6	4	3	1	2	5
K11	3	4	1	6	2	5
K12	6	5	2	3	1	4
K13	5	4	1	3	2	6
K14	6	2	5	1	4	3
K15	3	4	2	6	1	5
K16	6	5	2	3	1	4
K17	4	6	3	2	1	5
K18	3	5	2	4	1	6
K19	5	6	2	3	1	4
K20	6	3	1	2	5	4
	87	**89**	**39**	**65**	**41**	**99**
	0.20714286	0.2119048	0.0928571	0.1547619	0.097619	0.2357143
% weight	20.71	21.19	9.29	15.48	9.76	23.57