2nd International Conference on Advanced Composite Materials and Technologies for Aerospace Applications, June 11-13, 2012, Wrexham, UK

A Review of Cutting-edge Techniques for Material Selection

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Abstract: Selecting the optimum material for a given application is a complex task for engineers and designers across all industrial fields. There are a huge number of materials now available with a range of different properties and behaviours and so it has become even more necessary to carry out a systematic process in order to screen and/or rank the materials to give a promising number of candidates. The output of the material selection process depends upon which method is used. In some methods, a chart can be used to identify promising candidates whereas in others a single 'optimum' material may be chosen or a ranked list of candidates identified. This paper aims to summarise the documented techniques for material selection, evaluating the methods that are currently available, and compare the methods for consistency and effectiveness.

Key Words: Materials selection, Material screening, Performance indices, MCDM, TOPSIS, VIKOR, ELECTRE.

1. Introduction

Choosing the optimum material for an engineering application is a difficult but very important task. The selection of a cheaper material may mean greater competitiveness and more sales, the selection of a lighter material may increase fuel economy and reduce emissions in an automobile or aircraft, and the selection of an inappropriate material for a task may result in critical failure or poor performance. More recent demands from customers and legislation from governments have made material selection even more important. Examples of this include reducing the mass of a car in order to reduce emissions to meet regulations which are predicted to become tighter in years to come, and reducing the burden on a soldier by reducing the mass of the equipment that is carried.

There are over 160,000 materials available (Ramalhete et al., 2010), which gives an insight to the scale of the material selection task. Materials can be grouped into several general categories: Metals & Alloys, Polymers, Ceramics and Composites, with the materials inside each group usually having several properties in common. Each material is defined by its properties which are usually measured in tests carried out in accordance to standards (for example ISO or ASTM). These properties can be grouped into Mechanical Properties, such as Young's Modulus and Tensile Strength; Physical Properties, such as Density; Electrical, such as resistivity; Thermal, such as melt-ing point; and others, such as Cost. Some material properties have a quantitative value, such as the Hardness of a material measured by the Vicker's Hardness Test. Other properties can have a qualitative value often described in a linguistic nature, such as Corrosion Resistance being 'Poor', 'Good', 'Very Good', etc. These material properties are the profile used to compare one material against others for a given application.

With the huge range of properties that describe a material, it would be very rare to find a material that has the absolute ideal values for a function – instead, a trade-off of properties is usually required based on the requirements (Ashby, 2011). Material Selection Techniques are systematic tools that can aid a designer or engineer in defining the material requirements for a required function, and then finding the material that would suit this function best. Selection of a material should be investigated in parallel with initial design and product development, as the material selected will have individual properties that influence how it can and should be manufactured and therefore how it should be designed. Material Selection can also be used to identify alternative materials for an existing product, in order to reduce cost or mass or meet new legal requirements, for example.

The material selection techniques available vary in how they are used and the output of the method. In the method proposed by Ashby (2011), for example, the output is given on a chart with a calculated material performance index gradient that can be used to identify candidate materials. Others, such as the Multiple Criteria Decision Methods, are purely numerical and the output is often a screened, ranked shortlist of candidates which can then be investigated further.

This paper aims to research and review the documented material selection methods and their applications. In addition to this, the paper aims to consider other implications in the process, such as methods of identifying weightings of importance, and the material database resources available for the analyst.

2. Material selection methods

There are several documented methods that have been used for the selection of materials and these vary in function, from 'free-search' methods such as from Ashby (2011) to more quantitative methods such as the Weighted Property Method and the use of Multiple Criteria Decision Making techniques. In all methods, there is an importance in the first instance to fully understand the problem, so that the requirements and objectives can be selected carefully. Failure to understand the problem can result in a selection method giving unreasonable or even impossible solutions to a material selection problem.

Jahan et al. (2009) discovered that, at the time of research, the most popular methods documented for material selection were TOPSIS, ELECTRE and AHP, all techniques within the Multiple Criteria Decision Making (MCDM) methodology. There is a need to select a suitable method in accordance to the nature of the material selection problem (Cicek et al., 2010). In addition to the available methods, there are many academic papers that focus on modifying the traditional approaches or applying modified approaches to material selection problems. Some of the alternative approaches discovered will be discussed in this paper.

2.1 Ashby free-search

Ashby (2011) states that any given component desires a profile of material properties in order to function optimally. Clearly, however, it would be unrealistic to expect the exact profile of required properties to meet the property profile of a material. This means that some property trade-offs are required in order to find the overall most appropriate candidate material. Ashby (2011) defines a 'translation' step, where the requirements of a design are converted into constraints and objectives which can then be used to identify materials. Once these constraints are found, they can be applied to a material database (some example databases are identified later in this paper) in order to screen for potential candidates. These screened materials are then graphically shown according to a design objective or performance index, for example having the lowest cost or density, or the highest thermal conductivity, or a combination of a number of material properties (Ashby, 2011). No material selection technique can promise to give the perfect answer and so further research from documentation is required. This is important with aspects such as bi-metallic corrosion properties, manufacturing processes, availability, surface coatings, supplier relations, and other variables that are not assessed in the selection process. Fig. 1 shows a basic flow chart of the strategy proposed by Ashby (2011).

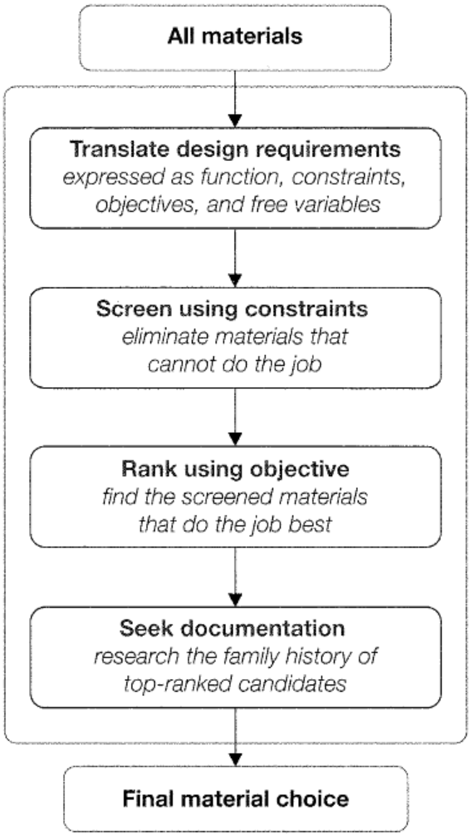

Figure 1. The strategy proposed by Ashby in four main steps (Ashby, 2001)

Parate and Gupta (2010) used Ashby's approach to choose a suitable material for an electrostatic actuator. Performance indices were developed for the component based on Ashby's methodology and material selection charts were used to find the best material candidates. It was noted in the paper that there is an ever-expanding database of materials available and the charts allow for new materials to be added. Parate and Gupta (2010) used selection charts with variables of Actuation Voltage vs. Speed and Fracture Strength vs. Displacement. They identified the best candidate materials for two actuator types - high actuation force and high actuation speed.

The method proposed by Ashby (2011) has the advantages of being intuitive and also relatively simple with a limited amount of calculations. CES Selector software from Granta, developed with Ashby, combines Performance Index generation and Material Selection Charts with a developed Material Database to allow a capability of carrying out the full selection technique efficiently in one piece of software.

Disadvantages of the Ashby method are that it requires a significant amount of work to calculate performance indices, select the required chart axes and then create the material selection charts. The procedure is not as systematic as some other methods, and it also does not give a ranked list of alternatives or assign a value of suitability. The CES Selector software from Granta does give a good solution to some of these issues as it contains several material databases, such as CAMPUS and Material Universe, as well as allowing for performance index calculations, creating selection charts and inputting gradients onto the charts based on performance indices. The output is still a chart, however, which can mean it is difficult to choose the optimum material(s) for a solution. Fig. 2 shows a material selection chart with gradients from performance indices overlaid. It is clear to see the material families and how the properties (Young's Modulus and Density in this case) are similar in each group.

2.2 Weighted Property Method

The Weighted Property Method is a very simple numerical decision-making technique. Firstly, the functions of

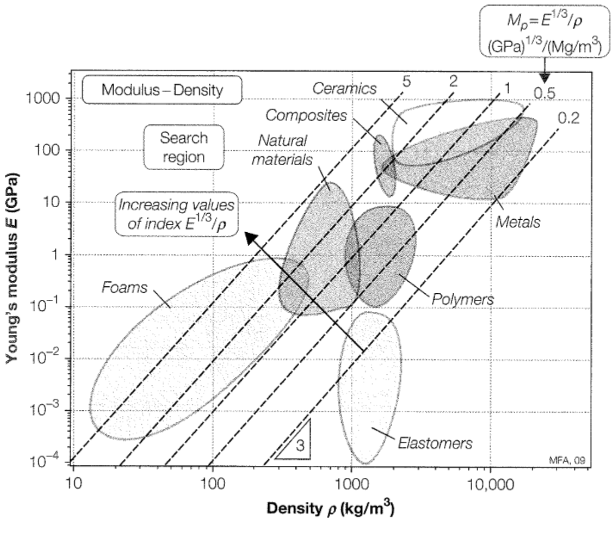

Figure 2. An example material selection chart showing Young's Modulus against Density, with performance index gradient lines shown (Ashby, 2001)

the application are assessed and each important attribute (material property) is then assigned a weighting of importance. These weightings are assigned by a designer/ engineer/etc. and the sum of all of the weightings should be equal to 1. Each material property has a unique scale of measurement, such as Tensile Yield Strength in MPa and Young's Modulus in GPa (SI units), so it is necessary to scale the numbers to allow an overall comparison index to be calculated. In order to obtain these scaled property values, a simple calculation is done. In material properties where a larger value is favoured, the numerical value of each property is divided by the largest value of that property across all candidate materials, and multiplied by 100. For material properties where a smaller value is more favourable (for example density or cost), the lowest value is divided by each value and multiplied by 100 (Findik and Turan, 2012). In order to find the weighted property index for each material, the scaled property values are first multiplied by the assigned weighting factor, to give the weighted scaled values. The weighted property index is then the sum of all of the weighted scaled values for each candidate material. This index can be used to compare any number of materials for suitability in the application. In cases where a qualitative value is given for a property, this can be converted to a quantitative value by applying a scale (Findik and Turan, 2012). For example, a corrosion resistance of 'Excellent' could convert to a value of 5, 'Very Poor' to a value of 1 and other linguistic values in-between.

An advantage of this method is its simplicity – a spreadsheet can be created using this method in minutes and any number of materials can be evaluated. It can also take into account any number of material properties and does not involve difficult arithmetic or expensive software. The output of the method also gives numerical values and this allows a ranked shortlist to be created and also means that the suitability of each material can be compared.

The method is completely reliant on the weighting values, as these define the importance of each property for the function. This means that change in the weightings results in a change in the selected material and so there is the problem of bias and mistakes in the weighting values. Actually selecting the weightings, where there is no 'right answer' also gives a further question – how can we obtain weightings that truly portray the requirements of the application? Importance weighting methods are discussed later in this paper.

Findik and Turan (2012) used this technique, as well as design considerations and joining methods, to identify materials that would allow the reduction in weight of a train load wagon. Required properties for the function included high specific strength and stiffness, corrosion resistance and low cost. Aluminium, magnesium and titanium alloys were considered as substitutes for the steel wagons and Al-alloys were selected as the most suitable by using the Weighted Property Method.

2.3 Multiple Criteria Decision Making

Multiple-Criteria-Decision-Making (MCDM) processes were not initially created for material selection; however material selection does fit well in the methodology. The MCDM technique involves generating alternatives (e.g. from a material database or from gathering data), establishing the required criteria and evaluating the alternative materials using a set of criteria weights; the outcome is a ranked list of alternative solutions (Jahan et al. 2009). A number of MCDM methods are reviewed in this section.

2.3.1 TOPSIS

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method is based on the factor that the chosen alternative (material) should have the shortest distance from the ideal solution and the longest distance from the negative-ideal solution (Opricovic and Tzeng, 2004). Shanian and Savadogo (2006) state that there are a number of features of TOPSIS which give it good potential for a material selection problem. The method allows for an unlimited number of alternatives (materials) and attributes (material properties), and it allows for trade-offs due to the fact that no attribute is considered alone – it is always seen as a trade-off with others. The output of TOPSIS is a ranked list with a numerical value for each alternative – allowing comparisons of suitability – whereas other techniques may only give the list. The method uses a pre-determined set of weighting criteria which are defined by the analyst/engineer. Pair-wise comparisons are avoided which means that the method is fast and allows for linking a database to the method, making it systematic and fast (Shanian and Savadogo, 2006).

The TOPSIS procedure starts with normalising the material property values to eliminate differences in units and applying weightings to create the weighted normalised decision matrix. Ideal and negative ideal solutions are then determined – in a case where a higher value is better, the highest value in the set of alternatives is chosen as the ideal (e.g. tensile strength), whereas the lowest value is chosen where this is desirable (e.g. cost). If ideal values of material properties are known (e.g. a known CTE value to match an optical housing to a lens) then this value can also be used. The separation from the ideal and anti-ideal solutions is then calculated to give the relative closeness to the ideal solution and this enables a ranked list of alternatives to be determined (Opricovic and Tzeng, 2004).

2.3.2 VIKOR

Vise Kriterijumska Optimizacija Kompromisno Resenje (VIKOR), like TOPSIS, works by ranking and selecting from alternatives based on the criteria and uses the approach of closeness-to-ideal. This technique is very similar to TOPSIS however there are differences and these have been discussed by Opricovic and Tzeng (2004). One difference is how the methods use normalisation of the material property values. VIKOR uses a linear normalisation where the normalised value does not depend on the evaluation unit of the criterion, whereas TOPSIS uses vector normalisation where the normalised value can change for different evaluation units of a particular criterion. The aggregation function of each method is also different – VIKOR uses a function that factors in only the distance from the ideal value and TOPSIS uses the ideal and anti-ideal values. The material property being as far from the anti-ideal value may not be a goal and so using

VIKOR may be a more effective approach. Both of the techniques produce a ranked list of alternatives – the optimum alternative in VIKOR is the closest to the ideal, the optimum in TOPSIS has the best ranking index (calculated from the distance of both the ideal and anti-ideal values) (Opricovic and Tzeng, 2004).

VIKOR allows the analysis of the impact of modifying the importance weightings in the calculation (Opricovic and Tzeng, 2004). This allows some stability analysis in the results, reducing the possible bias in the chosen weighting values and being advantageous when the analyst is unsure of the weighting preference for each criterion.

2.3.3 ELECTRE

There are numerous forms of ELECTRE that exist, including ELECTRE I, II, III, IV and TRI, and these forms all use the same fundamental concepts but differ in operation and depending on the type of problem (Marzouk, 2011). According to Marzouk (2011), ELECTRE outperforms other MCDM methods due to its ability to use inaccurate and uncertain data – such as material properties or weightings. This is important in material selection as there are often uncertainties in the measurement of material properties (Shanian et al., 2008) and in the relative importance values of each property. ELECTRE is non-compensatory – meaning separate material properties cannot compensate for each other (Shanian et al., 2008). For example, a good Tensile Strength value does not compensate for a poor Young's Modulus. This is very different from the Weighted Property Method, for example, where the performance of a material is governed by the sum of the weighted material properties.

Shanian et al. (2008) suggest that the goal of MCDM in material selection should be to not only identify materials with high rankings, but to also ensure that the materials have the most stable ranks over several design scenarios. Sensitivity analysis in a revised Simos' importance weighting method (discussed later in this paper), combined with a post-operation group decision-making process using ELECTRE III is used by Shanian et al. (2008). Their findings showed that the approach allows the identification of materials with both high and stable ranks – two important requirements in the decision making process. They suggested that further study into applications of the proposed method would be worthwhile to further analyse it's effectiveness.

Shanian and Savadogo (2006) used ELECTRE IV for material selection of bipolar plates in a polymer electrolyte membrane fuel cell. ELECTRE IV was used due to the non-compensatory nature of the technique. Their findings suggest that ELECTRE IV is a worthwhile method for material selection and the results obtained agreed with available reported results for the component. Jahan et al. (2009) found that ELECTRE techniques have limitations of high amounts of calculations with increased number of alternatives, and ELECTRE does not give a comparable performance value for each alternative, it only gives the ranked shortlist.

2.3.4 AHP

Analytical Hierarchy Process (AHP) is a method that discriminates between alternatives where inter-related objectives should be met. It is based on straightforward maths formulae and is used in a range of fields (government, industry, education, etc.) for decision-making (Mayyas et al., 2011). AHP works by structuring the decision problem into a hierarchy of sub-problems which can be analysed. The decision-maker then compares the elements of the hierarchy against each other by pair-wise comparison. The alternative (material) with the highest importance is the optimum. As AHP uses pair-wise comparison, it is infeasible for use in a situation with a high number of alternatives and/or criteria, where other MCDM methods such as TOPSIS would be more suitable (Jahan et al., 2011).

AHP is an attractive technique for combining opinions from several groups of experts – either for obtaining criteria weights or for the final selection. According to Jahan et al. (2011) the stand-alone AHP technique has less attention than techniques integrating AHP with other methods, such as SMART (Edwards and Barron, 1994) which combines AHP with the simple additive weighting method. Mayyas et al. (2011) used AHP and Quality Function Deployment (QFD) in selecting a material for an auto-motive body-in-white. They found that QFD was the superior technique, but that AHP provides systematic selection and gives numerical priority vectors to the material candidates.

2.4 Preferential ranking methods

(Chatterjee and Chakraborty, 2012) state that although various MCDM methods have been successfully applied to material selection problems, there is still a requirement to search for other tools and techniques for accurate ranking of alternative materials in a given engineering application. Four alternative methods based on preference-ranking are proposed by Chatterjee and Chakraborty, (2012) for use in material selection (EXPROM2, COPRAS-G, ORESTE and OCRA), and applied to solve material selection for a gear. All of these proposed methods have the output of a list of best-to-worst suitable materials based on the criteria. The research from Chatterjee and Chakraborty (2012) shows that the four investigated methods have high potential in material selection problems. It was noted that the best and worst suited materials found by each of the trialled methods was the same, giving a good indication of consistency and showing that the preference ranking methods can be applied to any type of material selection problem. Further research into the applications of these four proposed methods would be valuable.

3. Material databases and data gathering

Any material selection method that is chosen requires data to give a property profile of the materials that are to be evaluated. Material data is available from several sources such as from material suppliers, manufacturing companies, consultants, internal sources (e.g. in-house testing) or from a database. Already-constructed databases provide a quick and efficient way of obtaining material data, however the data source should also be considered when assessing the accuracy. Material suppliers usually have their own database of data, however this will be limited to the materials that the company provides and so many suppliers will need to be researched in order to obtain the data required which is time consuming. In-house testing can be a lengthy and expensive process and the material samples need to be obtained first – for this reason it should not be used to fill an entire database for material selection but it could be used to further test promising materials for data that could not be obtained from other sources. Some material databases are reviewed here.

3.1 Granta CES selector software

Granta CES Selector combines a material selection utility involving charts and performance indices, with material databases such as Material Universe and CAMPUS plastics. The database has generic materials rather than tradename materials and the values are given in ranges rather than one specific value, to include all of the materials available of this type. Suppliers of each material are also listed to enable the user to efficiently purchase some material or contact the supplier for more information if required. The Material Universe covers a wide range of polymers, ceramics, metals and alloys, and composites. According to Ramalhete et al. (2010), there are over 3700 materials in the Selector Basic Edition database which includes most types except for Textiles, “Smart” materials, Aerogels and Nano-materials. There are more versions of the CES software such as the Polymer Selector, Aero Selector, Eco Selector and Medical Selector which offer more materials in the database. The database also includes information on fabrication and production processes such as Injection Moulding and Welding.

3.2 Matweb

At the time of writing, Matweb Online Materials Information Resource has data sheets for over 88,000 materials including metals, polymers, ceramics and composites. Ramalhete et al. (2010) carried out research on the digital tools available for material selection and found there were 74,000 materials available in Matweb – meaning that there has been an addition of 14,000 more materials in just two years. Matweb provides the highest number of different materials in the database, however there are other digital tools which are discussed by Ramalhete et al. (2010) such as IDES Prospector and Polymat.

The research from Ramalhete et al. (2010) gives substantial information on the digital tools and databases available and further investigation into more of the databases would be worthwhile. They classified the different databases into ‘general’, where more than one material family is included and ‘spe-cific’ which focuses on one class or subclass of material.

4. Property weighting methods

Determining the weights of criteria (material properties) is an important task in most material selection methods, especially in Decision–Making techniques. Weighting the properties is subjective –it requires input of opinion from a decision maker which is then translated into quantitative data. The importance weightings of the material properties define the requirement profile of the product/ component. MCDM methods, such as TOPSIS, rely on the importance weightings in choosing an optimum material – this means that any change in the weightings will directly affect which material is output. In TOPSIS, the weightings are multiplied by the normalised property values and then summed to give a material property index – the value used as a comparison against other materials (B. Dehghan-Manshadi et al., 2007).

Weightings are subjective to the analyst that is applying them and this means that the designated decision-makers in the process should be chosen carefully. In the first instance, the material properties to be included in the weightings decision need to be chosen. The choice of important material properties to include depends upon the nature of the product or component or may depend upon whether the material property is intrinsic (such as Young’s Modulus) or can be modified or designed in a way that counteracts the property (such as corrosion resistance and coefficient of thermal expansion). Bias can occur in material selection if specific group(s) of properties outweigh other included group(s), for example having 3 thermal properties (thermal conductivity, diffusivity and CTE), against 1 mechanical property (e.g. tensile strength). Even if the 3 thermal properties have a low weight, they may outweigh the 1 mechanical property and it must be ensured that this meets the functional requirements and objectives of the product. As many material selection techniques are very sensitive to weightings values, it is very important to obtain the most accurate values for weights. It is possible that an individual is designated to decide on the values, or a group of people, or separate individuals onto which some statistical calculations are carried out. Due to the wide-ranging implications of material change(s) in a business setting, it may be necessary to include analysts from several disciplines, for example Mechanical Design, Business Groups, Manufacturing Engineers and Material Scientists. For some analysts that do not have the suitable material knowledge to make a decision, information will need to be provided to them in order for them to make a decision on the weightings. Identifying these very important values is difficult but essential. Sensitivity analysis can also be carried out in some selection methods, such as in the case of research by Shanian et al. (2008). The weighting process can be done for an entire product, a component, or even parts of a component which can be split into a hybrid structure – this is more likely in a situation where materials in a current product are being re-evaluated for an identified benefit.

There have been a few proposed systematic methods of assigning weightings to criteria and these are reviewed in this section.

4.1 Simos’ Card Play method

The card-play method proposed by Simos (1990) aims to obtain importance weightings for criteria using a hierarchal technique rather than assigning numbers from the outset, while also giving the decision-maker the informa-

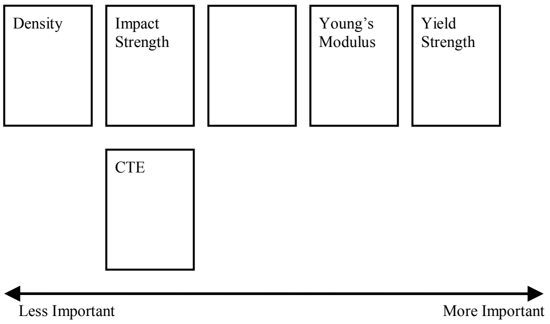

Figure 3. A schematic for Simos' Card-Play method

tion needed in order to decide on the weightings. The method Simos proposed is a simple and practical procedure that uses a set of pre-made cards to determine the numerical values of weightings indirectly and is a quick method of obtaining valuable information (Figuiera and Roy, 2002). The process works by firstly producing a set of cards with all of the criteria and any other necessary information for defining its importance. Designated analysts then rank the cards in order of importance, as shown in figure 3. Cards can be more important than others (on the right), or of the same importance (same horizontal level). Blank cards can then be placed between two successive cards to show even greater importance. For example, 1 blank card between 2 criteria cards means twice the difference between the criteria (Figuiera and Roy, 2002). After obtaining the ranked list of cards, a simple algorithm is used to assign numerical values to the criteria weightings.

Figueira and Roy (2002) found some problems with Simos' method and constructed an adapted procedure. One identified problem was that there is a piece of information lacking from Simos' procedure – the importance of the 'best' card compared to the 'worst' – i.e. how many times more important the most crucial criteria is compared to the least crucial. The modified technique from Figueira and Roy (2002) uses the same data collection method as Simos' original method; however the algorithm for calculating weights is modified to include a value 'z' – the ratio of importance of the highest ranked criterion to the lowest. The revised method also has some changes concerning rounding-off of figures in an optimal way and eliminating misprocessing of the blank card values. Figueira and Roy (2002) noted that their adapted technique has been applied successfully to real-life contexts, such as public transportation problems and environmental problems, and proved to be successful.

4.2 Digital Logic (Pair-wise comparisons)

The Digital Logic (DL) approach of weighting does not consider all criteria at the same time. Instead, the method uses comparisons between every pair of criteria, identifying which is most important in each case, to then find the overall most important and least important criteria for the requirements. For each pair to be evaluated, the maximum number of decisions is $N = n(n - 1)/2$, where n is the number of criteria (properties) being considered (B. Dehghan-Manshadi et al., 2007). A matrix can be constructed using the number of decisions required to fully evaluate every criterion. If the property to be evaluated is more important than the property it is being compared against, this column is assigned a '1', if it is less important, it is assigned '0'. The evaluation can be done by one individual, by a collaborative group, or by separate entities, on which some statistical analysis is carried out. To convert the DL matrix into weightings values for the Material Selection process, the values are scaled depending on whether it is beneficial to have a large or small value of each property.

A problem with the traditional DL method, found by Dehghan-Manshadi et al. (2007) is that if a property is found to be less important than every other, then it has acquired values of 0 in every comparison. This means that the overall weighting will then be 0 and it will not be of any importance in the material selection and is expelled. A modification by Dehghan-Manshadi et al. (2007) introduces relative values to DL – with a value of 1 assigned to a less important property and 3 to a more important one – ensuring that the least important remains in the selection list. Dehghan-Manshadi et al. (2007) used the modified version with the Weighted Property Method (WPM) and successfully applied it to material selection of a cryogenic tank and for a wing spar of a Human-Powered-Aircraft (HPA). The method provided more reasonable solutions for the wing spar than the existing WPM method.

5. Conclusions

There are numerous tools and techniques available to aid in material selection decisions. These include graphical techniques such as that proposed by Ashby, numerical techniques such as the MCDM methods, and also digital tools such as Matweb and Granta CES Selector. In addition to each individual technique, there are also several integrated or adapted methods that have been documented for material selection in order to improve the process. Despite the large amount of MCDM and other material selection methods available, no technique can be considered the most appropriate for any situation (Jahan et al. 2011) therefore it is necessary to understand the techniques in order to make a choice on which is most appropriate.

Several methods have been demonstrated to produce different outcomes in ranking a set of alternative materials/decisions. Jahan et al. (2011) propose that their aggregation method in MCDM has been developed to fill this gap, enhance the reliability of the chosen material and allow more robust decisions in material selection. There are also other integrated methods such as that proposed by Shanian et al. (2008) and Dehghan-Manshadi et al. (2007) as-well as others. There are some other documented methods that would be worthwhile to research further, these include: Z-transformation in statistics for normalisation of material properties (Fayazbaksh et al., 2009); Preference selection index method (Maniya and Bhatt, 2010); a novel method based on CES, adapted value engineering techniques, and TOPSIS (Thakker et al., 2008); Material filtration with multi-materials design (Giaccobi et al., 2010).

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