JMEPEG (1997) 6:359-364

A Novel Procedure for Selection of Materials in Concept Design

P. Dewhurst and C.C. Reynolds

This work is concerned with the selection of materials for conceptual product design prior to precise definition of part geometries. The proposed selection method is based on normalized scales of 0 to 100 for all fundamental material properties. The proposed scales are independent of the units which are used for the material property values. Three important transformations of the scales are demonstrated. First, the inverse material property is simply represented by 100 minus the original scale value. For example, if a material scores 83 for weight, then its scale value for lightness is 17. Second, a procedure is given for transformation the "100-scales" of individual properties to the "100-scale" of any derived parameter. Finally, a general procedure is established for the selection of multiple parameters with weighting values if desired. A spreadsheet sample database is presented suitable for teaching or demonstration purposes.

Keywords
cost estimation, fabrication costs, materials costs, requirement definitions

1. Introduction

THE RELATIONSHIPS between material properties and part processing capabilities and limitations make the selection of materials for a new product design difficult and complex. For example, if a structural member shaped as a "C" has to support a tensile load, then the designer knows that tensile yield stress will be important. However, it is difficult to define this need in precise quantitative terms because of the relationship between tensile load, tensile stress, and part geometry, and because the geometry will be dictated to a large degree by the chosen material and its process. In this case, bent steel tubing or a curved cast iron "T" section may be alternative solutions, but with different cross-sectional areas and wall thicknesses. For this reason, a procedure which is based upon a ranking of material properties would be much more appropriate for early design decision making than extensive lists of precise material property values found in handbooks (Ref 1-3) and software material databases (Ref 4). In the procedure developed by the authors, all fundamental material properties are divided into a scale of 0 through 100. Thus, for the tensile support member described above, a designer may simply indicate that 50 or better is required for tensile yield stress. Materials which satisfy this requirement can then be compared according to this or other property requirements.

The other aspect of material selection which is a great source of difficulty is the distinction between the fundamental material properties that are given in material databases and the actual design requirements, which are usually based on a combination of different property values. For the present purposes, material cost per unit weight will be included as a property of the material, so that economic constraints on design can be considered in the same manner as weight constraints, strength constraints, and so on. Thus, for a structural member in an aerospace product the designers may be interested in maximum stiffness per unit weight, while for a high-volume consumer product, maximum stiffness per unit cost may be more important. In the first case, the materials would be compared on the basis of a function of Young's modulus divided by density, and in the second case a combination of Young's modulus, density, and cost per unit weight would be the appropriate derived parameter for comparison purposes. Some derived parameters which are commonly used in mechanical design have been established in the literature (Ref 5, 6). The present work is concerned with developing a simple procedure for comparing materials based on either single fundamental properties or one or more derived parameters. Such material comparisons may typically be required on the basis of total performance, best performance per unit weight, or best performance per unit cost.

An important aspect of the work is the ability to compare materials for their ability to satisfy two or more different material performance requirements. This is intended to assist designers with minimization of parts in a design, through combination of parts into single manufactured components which may then be required to satisfy different design requirements. For example, if an initial design proposal has a structural member and a separate thermal insulator which are candidates for possible combination, then the designer will wish to compare the performance of materials based on the combined qualities of structural stiffness plus thermal insulation. The purposes of this work are thus to determine if materials exist which will satisfy several requirements in one part and to compare different materials on a normalized scale.

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2. Distribution of Material Properties

It has been observed by the authors in their work on computer-aided material and process selection (CAMPS) (Ref 7, 8) that material properties tend to be distributed approximately uniformly when presented on logarithmic scales. This fact can be seen clearly in the work of Ashby (Ref 6) in which material properties are plotted on a variety of combinations of logarithmic scales, such as yield strength plotted against density, coefficient of expansion against thermal conductivity, and so on. In

all cases the properties of groups of material represented as bubbles are seen to spread out in an approximately uniform manner across the logarithmic scales. For example, Fig. 1 shows the spread of the property of density for the different classes of materials when presented on a linear scale. It can be seen that there is a crowding of materials at the beginning of the scale, with poor discrimination between material properties in that region because of the coarse scale. Figure 2 shows the same data represented on a logarithmic scale which separates out the material classes somewhat uniformly across the wide range of property values. The same type of approximate log-uniform distributions is found to apply also to derived material properties.

Property distributions of the form shown in Fig. 2 can be changed to a log-linear scale through a transformation of the form

$$P = \alpha 10^{\beta N} \quad \text{(Eq 1)}$$

where P is the actual property value, N is the log-linear scale value, and α and β are the constants for a particular material property. In previous work by Ma and Dewhurst (Ref 8), α and β values were determined to represent properties on an A to F scale which were then manipulated internally in the CAMPS program using a corresponding scale of 1 to 6. However, in order to fit the wide range of property values into only six categories in CAMPS, values were allowed to spill over the tops of the scales as A's (or A+'s) and off the bottoms of the scales as F's (or F–'s). For the operation of the CAMPS program this does not matter since the numerical values are hidden. However, in the present work, look-up tables are proposed in which fixed upper and lower values provide benchmarks for comparison of material properties. These fixed values for the material properties will be set at zero for the least value in the material database and at 100 for the highest value. The database will then be updated automatically if a new material is introduced with a higher or lower property value than any of the existing materials. However, these extreme materials are in most cases unlikely to be exceeded.

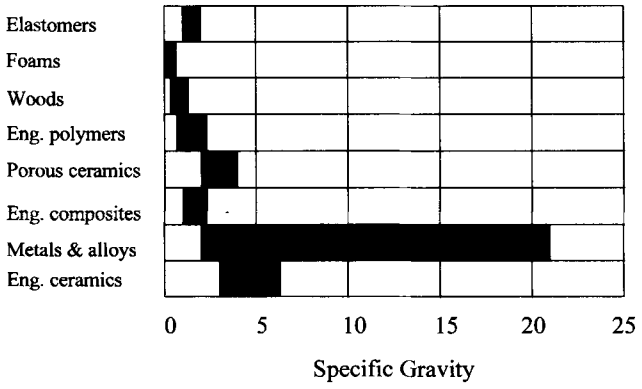

Fig. 1 Typical linear distribution of material properties

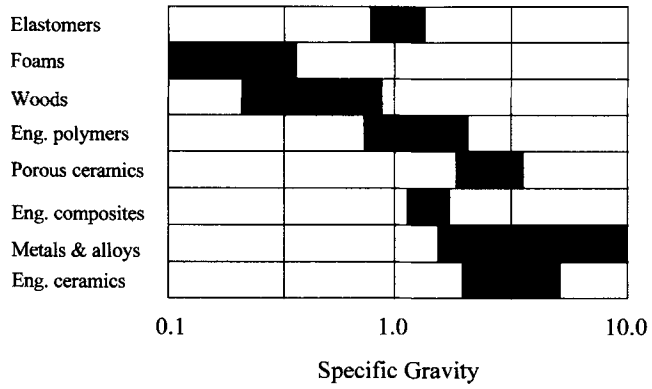

Fig. 2 Typical logarithmic distribution of material properties

Consider property P and let P_{max} and P_{min} be the highest and least values in the database, respectively. Thus from Eq 1:

$$\alpha = P_{min} \quad \text{(Eq 2)}$$

$$\beta = \log(P_{max}/P_{min})/100 \quad \text{(Eq 3)}$$

Substituting Eq 2 and 3 into Eq 1 gives:

$$N = 100 \log(P/P_{min})/\log(P_{max}/P_{min}) \quad \text{(Eq 4)}$$

For example, for Young's modulus, E, the largest value in the database is likely to be the value for diamond, which gives:

$$E_{max} = 1.5 \times 10^8 \text{ lbf/in.}^2$$

while the least value may be the value for natural rubber, which gives:

$$E_{min} = 6.65 \times 10^2 \text{ lbf/in.}^2$$

With these values the "100-scale" for Young's modulus is given from Eq 4 as:

$$N = 18.68 \log (0.001504\, E) \quad \text{(Eq 5)}$$

where E has units of lbf/in.^{2}.

Table 1 gives N values for Young's modulus for a small range of commonly used materials. It can be seen that the values appear to represent an engineer's perception of material stiffness. In particular, values greater than 50 apply to materials which are found in structural applications.

Table 1 "100-scale" values for Young's modulus

Material name	*N*
Diamond	100
Tungsten carbide	95
Steel	87
Magnesium	75
Polycarbonate (33% glass)	64
Pine (parallel to grain)	61
Particle board	51
High-density polyethylene	42
Urethane foam	26
Cork	12
Natural rubber	0

Largest and least values for a range of principal fundamental material properties are given in Table 2. A small material database is given in Table 3, which includes representative materials from metal alloys, polymers, rubbers, foams, ceramics, and natural materials. Table 4 gives "100-scale" values for the properties included in the Table 3 database. The additional data on the bottom three rows and on the last two columns of Table 4 are discussed in the next section.

3. Derived Parameters and Log-Linear Scales

A number of derived parameters of importance in mechanical design (Ref 5, 6) are given in Table 5. They can be represented by the general form

$$D = P_1^{m_1} P_2^{m_2} P_3^{m_3} \ldots \quad \text{(Eq 6)}$$

Table 2 Largest and least material property values

Property	Material name	Largest value	Least value	Units
Tensile yield strength	Alloy steel (4130)	200,000	...	lbf/in.^{2}
	Cork	...	145	lbf/in.^{2}
Compressive strength	Tungsten carbide	717,500	...	lbf/in.^{2}
	Cork	...	145	lbf/in.^{2}
Young's modulus	Diamond	1.5×10^8	...	lbf/in.^{2}
	Rubber	...	665	lbf/in.^{2}
Thermal conductivity	Diamond	1387	...	Btu/(h · ft^2 · °F)
	Cork	...	0.020	Btu/(h · ft^2 · °F)
Coefficient of linear expansion	Cork	1.3×10^{-4}	...	in./in.
	Diamond	...	8.0×10^{-7}	in./in.
Specific heat	Rubber	0.50	...	Btu/(lb · °F)
	Copper	...	0.092	Btu/(lb · °F)
Density	Tungsten carbide	0.48	...	lb/in.^{3}
	Cork	...	0.005	lb/in.^{3}
Cost	Industrial diamond	330	...	$/lb
	Concrete	...	0.06	$/lb

Table 3 Representative materials

Material name	Cost, $/lb	Tensile yield strength, lbf/in.^{2}	Elastic modulus, lbf/in.^{2}	Compressive yield strength, lbf/in.^{2}	Thermal conductivity, Btu/h · ft^2 · °F	Specific heat, Btu/lb · °F	Density, lbf/in.^{3}
Gray cast iron (A48)	1.60E–01	4.25E+04	1.95E+07	4.25E+04	2.90E+01	1.30E–01	2.60E–01
Aluminum (201, solution treated)	3.20E+00	6.50E+04	1.00E+07	5.60E+04	7.00E+01	2.30E–01	1.00E–01
Copper (C82000, as cast)	4.50E+00	7.50E+04	1.70E+07	7.50E+04	1.50E+02	1.00E–01	3.11E–01
Magnesium (AZ91D)	7.70E+00	3.40E+04	6.50E+06	3.40E+04	3.10E+01	2.45E–01	6.50E–02
Mild steel (c.q., cold formed)	4.50E–01	6.20E+04	3.00E+07	6.20E+04	2.70E+01	1.10E–01	2.80E–01
Alloy steel (high strength 4130)	6.10E+00	2.00E+05	3.00E+07	2.00E+05	2.50E+01	1.10E–01	2.83E–01
Aluminum (1100, half hard)	3.60E+00	1.70E+04	1.00E+07	1.70E+04	1.28E+02	2.20E–01	9.80E–02
Aluminum alloy (high strength 2036)	5.40E+00	2.80E+04	1.03E+07	2.80E+04	9.16E+01	2.20E–01	9.90E–02
Beryllium copper (C17200)	1.75E+01	1.60E+05	1.85E+07	1.60E+05	6.80E+01	1.00E–01	2.98E–01
Copper, hard (C10200)	5.10E+00	4.50E+04	1.70E+07	4.50E+04	2.26E+02	9.20E–02	3.23E–01
Nickel alloy (Inconel 825)	9.60E+00	3.60E+04	2.80E+07	3.60E+04	6.42E+00	1.10E–01	2.94E–01
Titanium (Ti-8Mn)	1.22E+01	1.37E+05	1.64E+07	1.37E+05	6.30E+00	1.18E–01	1.71E–01
Lead	1.30E+00	2.90E+03	2.20E+06	2.90E+03	1.99E+01	3.00E–02	4.10E–01
Acrylic (high impact)	1.38E+00	6.75E+03	2.80E+05	6.75E+03	1.20E–01	3.40E–01	4.10E–02
Epoxy (glass reinforced)	2.40E+00	9.50E+03	4.50E+05	3.60E+04	3.00E–01	4.50E–01	6.90E–02
Nylon (6/6)	1.58E+00	1.02E+04	4.30E+05	1.02E+04	1.40E–01	4.00E–01	4.10E–02
Polycarbonate (glass reinforced)	1.90E+00	2.30E+04	1.68E+06	2.10E+04	1.30E–01	3.00E–01	5.50E–02
Polyester SMC (glass reinforced)	2.12E+00	1.60E+04	1.75E+06	2.90E+04	1.25E–01	2.30E–01	6.20E–02
Polyethylene (high density)	8.00E–01	3.60E+03	1.20E+05	3.60E+03	1.90E–01	5.00E–01	3.50E–02
Rubber (isoprene)	1.58E+00	4.00E+03	6.65E+02	4.00E+03	8.20E–02	5.00E–01	3.50E–02
Polyurethane foam	8.00E–01	2.20E+03	1.56E+04	2.50E+03	3.00E–02	1.70E–01	1.80E–02
Advanced carbon composite	2.50E+02	1.40E+05	4.70E+07	7.00E+04	2.25E+03	1.60E–01	6.60E–02
Alumina	8.00E+00	2.50E+04	4.00E+07	2.70E+05	1.73E+01	2.00E–01	1.32E–01
Silicon carbide (sintered)	3.00E+01	1.00E+04	4.80E+07	1.50E+05	4.62E+01	3.20E–01	1.07E–01
Tungsten carbide (sintered)	1.20E+02	1.30E+05	7.82E+07	7.18E+05	4.25E+01	2.00E–01	4.80E–01
Glass (soda lime, general purpose)	1.50E–01	1.33E+04	1.06E+07	2.00E+05	5.80E–01	2.00E–01	8.90E–02
Particle board (medium density)	1.60E–01	2.25E+03	4.25E+05	2.10E+03	7.00E–01	5.00E–01	2.20E–02
Pine (parallel to grain)	9.30E–01	1.15E+04	1.20E+06	4.80E+03	2.30E–01	5.80E–01	1.30E–02
Diamond	3.30E+02	3.90E+04	1.50E+08	5.80E+05	1.39E+03	1.20E–01	1.27E–01
Cork	6.80E–01	1.45E+02	2.90E+03	1.45E+02	2.00E–02	4.80E–01	5.00E–03
Concrete	6.00E–02	2.40E+02	4.35E+06	3.60E+03	9.00E–01	2.30E–01	9.00E–02
Pottery	3.00E–01	4.80E+03	1.02E+07	7.25E+04	1.50E+00	2.00E–01	8.00E–02

Table 4 "100-scale" values

Material name or parameter	Cost	Tensile yield strength	Elastic modulus	Compressive yield strength	Thermal conductivity	Specific heat	Density	W	N
Gray cast iron (A48)	11	79	83	67	63	50	87	–0.228	41
Aluminum (201, solution treated)	46	84	78	70	70	69	66	0.090	62
Copper (C82000, as cast)	50	86	82	73	77	41	90	–0.326	34
Magnesium (AZ91D)	56	75	75	64	63	71	56	0.215	70
Mild steel (c.q., cold formed)	23	84	87	71	62	44	88	–0.198	43
Alloy steel (high strength 4130)	54	100	87	85	61	44	88	–0.203	42
Aluminum (1100, half hard)	48	66	78	56	75	67	65	0.099	62
Aluminum alloy (high strength 2036)	52	73	78	62	72	67	65	0.099	62
Beryllium copper (C17200)	66	97	83	82	70	41	90	–0.295	36
Copper, hard (C10200)	52	79	82	67	80	38	91	–0.342	33
Nickel alloy (Inconel 825)	59	76	86	65	50	44	89	–0.229	41
Titanium (Ti-8Mn)	62	95	82	81	49	46	77	–0.071	51
Lead	36	41	66	35	59	0	97	–0.742	7
Acrylic (high impact)	36	53	49	45	15	82	46	–0.040	53
Epoxy (glass reinforced)	43	58	53	65	23	91	58	–0.197	43
Nylon (6/6)	38	59	53	50	17	87	46	0.022	57
Polycarbonate (glass reinforced)	40	70	64	58	16	78	53	0.092	62
Polyester SMC (glass reinforced)	41	65	64	62	16	69	55	0.046	59
Polyethylene (high density)	30	44	42	38	19	95	43	–0.094	50
Rubber (isoprene)	38	46	0	39	12	95	43	–0.845	0
Polyurethane foam	30	38	26	33	3	59	28	–0.100	49
Advanced carbon composite	97	95	91	73	100	57	57	0.494	88
Alumina	57	71	89	89	58	64	72	0.170	78
Silicon carbide (sintered)	72	59	91	82	67	80	67	0.287	75
Tungsten carbide	88	94	95	100	66	64	100	–0.294	36
Glass (soda lime, general purpose)	11	63	79	85	29	64	63	0.149	66
Particle board (medium density)	11	38	52	31	31	95	32	0.291	75
Pine (parallel to grain)	32	60	61	41	21	100	21	0.669	100
Diamond	100	77	100	97	96	47	71	0.378	81
Cork	28	0	12	0	0	94	0	0.213	70
Concrete	0	7	71	38	33	69	63	0.015	57
Pottery	19	48	78	73	37	64	61	0.190	68
α	0.06	145	665	145	0.02	0.03	0.005	$W_{min} = -0.845$	
β	0.0374	0.0313	0.0535	0.0369	0.0505	0.0128	0.0198	$W_{max} = 0.669$	
m (index)	0	0	0.333	0	0	0	–1		

Table 5 Derived parameters for best performance

To obtain:	Maximum performance	Minimum weight	Minimum cost
Strongest tension member	Y_t	Y_t/ρ	$Y_t/(\rho C_m)$
Strongest compression member	Y_c	Y_c/ρ	$Y_c/(\rho C_m)$
Strongest beam or plate	Y_t	$Y_t^{0.5}/\rho$	$Y_t^{0.5}/(\rho C_m)$
Stiffest structural beam	E	$E^{1/3}/\rho$	$E^{1/3}/(\rho C_m)$
Best coil or tension spring	Y_t^2/E	$Y_t^2/(E\rho)$	$Y_t^2/(E\rho C_m)$
Best diaphragm spring	$Y_t^{1.5}/E$	$Y_t^{1.5}/(E\rho)$	$Y_t^{1.5}/(E\rho C_m)$
Best insulation	$1/K$	$1/(K\rho)$	$1/(K\rho C_m)$
Maximum heat storage	$\rho C_p K$	$C_p K$	$C_p K/C_m$

Y_t, tensile yield stress, lbf/in.^{2}; Y_c, compressive yield stress, lbf/in.^{2}; E, Young's modulus, lbf/in.^{2}; K, thermal conductivity, Btu/(hr · ft^2 · °F); ρ, density, lb/in.^{3}; C_p, specific heat, Btu/(lb · °F); C_m, material cost/weight

For example, in Table 5, if $P_1 = Y_t$, $P_2 = E$, $P_3 = \rho$, $m_1 = 2$, $m_2 = -1$, and $m_3 = -1$, then D is the derived parameter for best spring performance per weight.

Let the log-linear relationships for $P_1, P_2, P_3, \ldots$ be:

$$P_1 = \alpha_1 10^{\beta_1 N_1}$$

$$P_2 = \alpha_2 10^{\beta_2 N_2} \quad \text{(Eq 7)}$$

$$P_3 = \alpha_3 10^{\beta_3 N_3}$$

$$\vdots$$

The general form of a derived parameter then becomes:

$$D = (\alpha_1^{m_1}\alpha_2^{m_2}\alpha_3^{m_3}\ldots)10^{(m_1\beta_1 N_1 + m_2\beta_2 N_2 + m_3\beta_3 N_3 + \ldots)} \quad \text{(Eq 8)}$$

and we require that D is represented by:

$$D = \alpha 10^{\beta N} \quad \text{(Eq 9)}$$

where $0 \le N \le 100$.

Thus, from Eq 4, the "100-scale" value for the derived parameter is given by:

$$N = 100 \log(D/D_{min})/\log(D_{max}/D_{min}) \quad \text{(Eq 10)}$$

Equation 10 can be simplified further by recognizing that the factor $(\alpha_1^{m_1}\alpha_2^{m_2} \ldots)$ will cancel in the argument of both logarithmic expressions.

Thus define parameter W as:

$$W = m_1\beta_1 N_1 + m_2\beta_2 N_2 + \ldots \quad \text{(Eq 11)}$$

Substituting W into Eq 10 gives:

$$N = 100 \log(10^{W-W_{min}}/\log(10^{W_{max}-W_{min}}) \quad \text{(Eq 12)}$$

$$= 100\,(W - W_{min})/(W_{max} - W_{min}) \quad \text{(Eq 13)}$$

This transformation from "100-scale" values for individual parameters to the "100-scale" value for any derived parameter is easily accomplished on a spreadsheet using Eq 11 and 13. Table 4 is the printout of such a spreadsheet written with Microsoft Excel. The bottom three rows of the spreadsheet contain values for α, β, and m (the index values of the derived parameter), respectively. The last two columns contain the values for W and the "100-scale" N values for the derived parameter, respectively. The values for W_{min} and W_{max}, used in Eq 13, are given at the bottom of the W column.

Note that the index values entered into the last row are those for beam stiffness for minimum weight. It can be seen that for this application (and no other design constraints), straight-grained pine is the best choice ($N = 100$), advanced carbon fiber composite is the second best choice ($N = 88$), and rubber is the worst choice ($N = 0$). Note that manufacturing feasibility is not a part of this selection process. Thus, while diamond scores a credible 81, its use would obviously be restricted to very small and very expensive devices. If we change the index for cost from 0 to –1, then the derived parameter changes to represent beam stiffness for minimum cost; see Table 5. The best choice then changes to concrete, pine drops to a score of 85, advanced carbon fiber composite drops to 13, diamond drops to 6, and tungsten carbide drops to 0 because of its combination of high cost and high density. The main purpose of the "100-scale" method is for such easy visualization of the relative merits of materials for different applications.

4. Inverse Properties

Sometimes the choice of a material is based on the inverse of one of the fundamental properties. Examples would include specific volume representing lightness instead of density representing heaviness, thermal insulation instead of thermal conductivity, softness instead of compressive strength, and so on.

Assume we are interested in inverse property $(1/P)$ where P is represented by Eq 1. Let

$$(1/P) = \alpha_I 10^{\beta_I N_I} \quad \text{(Eq 14)}$$

From Eq 2 and 3, the values of α_I and β_I for the inverse property are given by:

$$\alpha_I = 1/P_{max} \quad \text{(Eq 15)}$$

$$\beta_I = \log\,[(1/P_{min})/(1/P_{max})]/100 \quad \text{(Eq 16)}$$

$$= \log(P_{max}/P_{min})/100 \quad \text{(Eq 17)}$$

and so the value for N_I becomes (Eq 4):

$$N_I = 100 \log\,[(1/P)/(1/P_{max})]/\log(P_{max}/P_{min}) \quad \text{(Eq 18)}$$

$$= 100\,[(\log(P_{max}/P_{min}) - \log(P/P_{min})]/\log(P_{max}/P_{min}) \quad \text{(Eq 19)}$$

$$= 100 - N \quad \text{(Eq 20)}$$

This result simply stems from the "100-scale" span from minimum to maximum values, which exchange places when the inverse property is considered. However, the fact that not just "100" and "0" change places, but that "95" becomes "5," "90" becomes "10," and so on, is intuitively satisfying.

Finally, it can be noted from Eq 1 and 8 that the inverse scale can be obtained by setting the index value, m, equal to –1:

$$1/P = 1/(\alpha 10^{\beta N}) = \alpha^{-1}10^{-\beta N} \quad \text{(Eq 21)}$$

5. Selection of Several Parameters

Assume several derived parameters (or fundamental properties) are to be considered in the choice of a material. Let the parameters be represented by:

$$D_1 = \alpha_1 10^{\beta_1 N_1}$$

$$D_2 = \alpha_2 10^{\beta_2 N_2} \quad \text{(Eq 22)}$$

$$\vdots$$

$$D_n = \alpha_n 10^{\beta_n N_n}$$

Since the values for D_1, D_2, ... may differ by several orders of magnitude, the use of an arithmetic mean is unlikely to provide a generally useful selection criterion. With an arithmetic mean, a given percentage change in a low-magnitude parameter will have less effect than the same percentage change in a high-magnitude parameter. Also, the difference between high and low magnitudes can be simply a function of the chosen units. A more sensible alternative is to use the concept of geometric mean, for which the same percentage change in any of the parameters of interest will have the same effect on the mean. In order to provide maximum flexibility in defining a se-

lection criterion, the geometric mean will be combined with a relative importance, or relative weighting system.

Let weightings $w_1, w_2, \ldots, w_n$ be applied to $D_1, D_2, \ldots, D_n$, respectively. The weightings are chosen to satisfy

$$w_1 + w_2 + \ldots + w_n = n \quad \text{(Eq 23)}$$

For a geometric mean, G, the weightings must be applied as exponents, so that:

$$G = \left(D_1^{w_1} D_2^{w_2} \ldots D_n^{w_n}\right)^{1/n} \quad \text{(Eq 24)}$$

Note that if $D_1 = D_2 = \ldots = D_n = D$ then the weighted geometric mean becomes:

$$G = \left(D^{(w_1 + w_2 + \ldots w_n)}\right)^{1/n}$$

$$= (G^n)^{1/n} = G$$

which is the necessary equality of any sensible weighting scheme.

Following the same steps as in section 3, we can write:

$$G = \left(\alpha_1^{w_1} \alpha_2^{w_2} \ldots \alpha_n^{w_n}\right) 10^{(w_1\beta_1 N_1 + w_n\beta_n N_n)/n} \quad \text{(Eq 25)}$$

and the "100-scale" value for G becomes:

$$N = 100 \log(G/G_{min})/\log(G_{max}/G_{min}) \quad \text{(Eq 26)}$$

Equation 26 can be simplified to be identical to Eq 13, provided that parameter W is redefined as:

$$W = w_1\beta_1 N_1 + w_2\beta_2 N_2 + \ldots + w_n\beta_n N_n \quad \text{(Eq 27)}$$

Note that Eq 27 and 11 are identical in form. Thus, the spreadsheet given in Table 4 can be used without change to select several parameters with associated weightings. The weightings can be assigned arbitrarily. For example, it might be considered that maximum strength is twice as important as maximum stiffness in the design of a tensile structural member. The weighting values would then be $w_1 = 4/3$ and $w_2 = 2/3$ for Y_t and E, respectively. The values for w_1 and w_2 were chosen to satisfy the 2:1 required relationship and also Eq 23. Note, however, that the latter requirement can be omitted, since any constant multiple of Eq 27 will cancel in the quotient of Eq 13. Thus, in the above example, setting $w_1 = 2$ and $w_2 = 1$ would produce the same "100-scale" results.

6. Discussion and Conclusion

A procedure is proposed for representing material performance properties in a database by a set of 0 to 100 scales. The "100-scales" have been shown to have several useful attributes. The scales are independent of the units used to describe the properties. The "100-scale" for an inverse property is simply 100 minus the original scale. Transformations of "100-scales" for individual properties into scales for derived parameters of interest, or into scales representing weighted combinations of individual or derived parameters, are easily performed.

A spreadsheet implementation of a "100-scale" database is included in the paper for demonstration purposes. This provides a useful teaching tool for illustrating the roles of different materials in mechanical design. For real design implementation the database would require substantial expansion to include other properties and a much wider range of materials.

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