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Material Selection for a Manual Winch Rope Drum

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Abstract**—**The selection of materials is an essential task in mechanical design processes. This paper sets out to demonstrate the application of analytical decision making during mechanical design and, particularly, in selecting a suitable material for a given application. Equations for the mechanical design of a manual winch rope drum are used to derive quantitative material performance indicators, which are then used in a multiple attribute decision making (MADM) model to rank the candidate materials. Thus, the processing of mechanical design considerations and material properties data into information that is suitable for use in a quantitative materials selection process is demonstrated for the case of a rope drum design. Moreover, Microsoft Excel®, a commonly available computer package, is used in the selection process. The results of the materials selection process are in agreement with current industry practice in rope drum design. The procedure that is demonstrated here should be adaptable to other design situations in which a need arises for the selection of engineering materials, and other engineering entities.

Keywords**—**Design Decisions, Materials Selection, Mechanical Design, Rope Drum Design.

I. INTRODUCTION

WINDLASSES, manual winches, power winches and cranes are commonly used hoisting equipment. A common feature among these devices is the use of a revolving drum, in conjunction with wire rope, to transform the turning force applied at the drum axis into a pulling force in the wire rope.

This paper addresses the design of a rope drum for manual winch application and, particularly, the selection of a material for such a drum. Ultimately the paper demonstrates the processing of rope drum design considerations and material properties data into information that can be used to select a suitable material for the manufacture of the rope drum. The selection procedure that is demonstrated here can be adapted and used in other situations where the selection of a material for a product under design is necessary.

II. METHODOLOGY

The problem of selecting a material for the manufacture of a product entails making the decision to use a particular material, picked from among the available candidate materials, such that the selected material will satisfy a variety of design, manufacturing and service requirements, in a manner that is perceived to be the most beneficial. A problem of this kind is known as a Multiple Criteria Decision Making (MCDM) problem.

Over the last about half a century, many methods for dealing with MCDM have been developed and used, at an increasing rate and in a variety of disciplines. Today, a substantial amount of literature is available that endeavors to analyze and compare the various MCDM methods and to identify their merits, demerits and suitability for particular applications. Jahan and Edwards [1] dwell on the application of MCDM methods to materials selection in product design.

Athawale and Chakraborty [2] used each of ten, commonly used, MCDM methods in three different materials selection cases and compared the agreement, or the lack of it, in the resultant rankings of the candidate materials, with respect to the different MCDM methods. They found that the rankings of the candidate materials were not significantly affected by the choice of MCDM method to be used. Thus, they recommended that the main focus should be laid, not on selecting an appropriate MCDM method to use, but rather, on identifying the relevant criteria to be used in selecting the material and the candidate materials to be included in the selection process.

In any case, once an MCDM method to be used has been selected, actual use of the method to select a material is reduced to routine that can be readily implemented on computer. Therefore, in a given materials selection problem, one can use a number of different MCDM methods and compare the resultant rankings, just as [2] did, before arriving at the final choice of material.

Given these circumstances, it should be more challenging and rewarding to scrutinize the design issues that are specific to the product being designed, in order to establish the relevant selection criteria, and to include the candidate materials, that would yield meaningful results, from a mechanical design point of view. Doing this, for the case of a rope drum design, is the main objective in this paper.

According to [3], the selection of materials in engineering design involves:

(1) Translating design requirements into specifications for a material,
(2) Screening out those materials that do not meet the specifications in order to leave only the viable candidates,
(3) Ranking of the surviving materials to identify those that have the greatest potential,
(4) Using supporting information to finally arrive at the choice of material to be used.

This paper is particularly concerned with the translation of design requirements into material performance ratings and the subsequent ranking of viable candidate materials by use of

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material indices of merit. It commences with a review of the mechanical design process, as applied to a rope drum, and elaboration of the pertinent design considerations, leading to the establishment of relevant design equations. The design equations are then used in translating design considerations into quantitative indicators of material performance. This is essentially an information processing task.

The problem of selecting a material for the rope drum is then formulated as a multiple attribute decision making (MADM) problem in which the normalized material performance ratings are the attributes. Material indices of merit are then calculated as weighted sums of the attributes. Application of the selection procedure is demonstrated using material properties data that were drawn from the literature.

III. REVIEW OF THE MECHANICAL DESIGN PROCESS OF A ROPE DRUM

In selecting wire rope, for instance, one only has to choose a rope that would best meet the application requirements, from a set of ready-made products whose details are specified in the manufacturers' catalogues [4]. This is often the case when dealing with highly standardized, mass produced components, amongst which are antifriction bearings, power transmission chains, V-belts and wire rope. In engineering design, the process of selecting such standardized components has been termed *application engineering* [5].

The capital-intensive mass production of highly standardized components is justified if such components are used in a wide range of applications. Thus they can be manufactured and sold in great quantities, with the accruing advantages of the economy of scale. This is true for most components of electronic equipment. On the other hand, components such as rope drums find application on only a small set of specialized equipment such as cranes and winches. Moreover, design requirements on rope drums may vary widely from one instance of application to another. Therefore, it would not be economical to standardize and mass-produce components that fall into this category. Thus, rope drums usually have to be designed from first principles and possibly be manufactured in-house. This is typical of most mechanical components that comprise the working head of machines.

The activities that comprise product design include the determination of materials, geometry and manufacturing processes, as well as the overall configuration of the product, so that it can be made and function to specifications.

The basic gross geometrical form of the rope drum is not in contention. It is usually a right circular cylindrical shell. The reasons for the choice of this form include the following:

- The curvature of the circular form is continuous and uniform and it is completely determined by a single parameter – the radius. Indeed, the circular form is completely symmetrical.
- The circular form is relatively easy to produce and there are a number of manufacturing processes that are suited for its production.
- The right circular cylindrical shell economizes on the weight of the drum.

Further, the design process aims, among other things, to simultaneously satisfy the following manufacturing and operating requirements:

- Minimum expenditure on labour, materials, energy and other resources, both in the manufacture and use of the product,
- Simple, convenient operation and servicing with minimum physical demands on personnel,
- Maximum productivity in using the device, with maximum efficacy and at minimum cost,
- Maximum reliability – so that the device can be relied upon to function as it should, when it is expected to.

The rope drum functions in conjunction with wire rope and therefore its design must always take drum-rope interactions into account. For instance, the active surface of the drum should preferably be provided with grooves that enable the rope to wind uniformly upon the drum. Moreover, where possible the whole length of rope should be accommodated in a single layer of winding upon the drum, to minimize rope wear. Thus, rope drum design aims at realizing a rope drum that meets the following, among other requirements:

- Store the entire length of rope in one smooth, even layer. This is realized by providing a suitable combination of drum diameter and drum length, which determine the area of the active surface of the drum.
- Avoid intertwining of the rope and minimize wear and other damage to the rope. This can be achieved by providing the active surface of the drum with suitable grooves of requisite dimensions for the diameter of the rope to be used, as well as selecting a suitable material for the drum shell.
- Be of adequate strength to withstand the most severe loading that is applicable. This can be achieved by providing adequate dimensions of the drum, such as the combination of drum diameter, drum length and drum shell thickness, as well as selecting a suitable material for the drum.
- Resist abrasion and corrosion. This can be achieved through proper selection and processing of material for the drum.
- Be of minimum cost possible. This can be achieved largely through the selection of materials and manufacturing processes.

From the above considerations, it is evident that the selection and processing of materials is a major task of critical importance in the design of a manual winch rope drum, just as it is in the design of most products.

IV. ELABORATION OF PERTINENT ROPE DRUM DESIGN CONSIDERATIONS

A. Drum Shell Thickness under the Rope

During operation, the drum is subjected to a combination of torsion, bending and compressive hoop stresses. Torsion and bending become significant only for very long drums. Since compressive hoop stress is much larger than stresses due to torsion and bending, it should be considered first.

Consider an element from the drum shell as illustrated in Fig. 1. D_d is drum diameter and d_r is wire rope diameter. The shell can be treated as a thin walled cylinder.

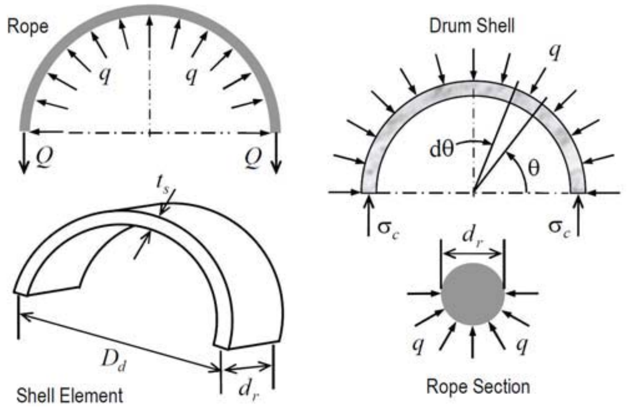

Fig. 1 Determination of drum shell thickness

Any frictional effects between the rope and the drum shell will be neglected and it shall be assumed that the pressure acting upon the drum shell due to the rope is uniform. With θ being measured in radians, the elemental area $\mathrm{d}A$ upon which the pressure q acts may be expressed as:

$$\mathrm{d}A = \frac{D_d d_r}{2}\mathrm{d}\theta \tag{1}$$

The force that acts normally upon this elemental area, due to pressure q, may be expressed as:

$$q\mathrm{d}A = \frac{qD_d d_r}{2}\mathrm{d}\theta \tag{2}$$

The vertical component of the above force is given by:

$$q\sin\theta\mathrm{d}A = \frac{qD_d d_r \sin\theta}{2}\mathrm{d}\theta \tag{3}$$

Now, consider the balance of vertical forces acting upon the semi-circular drum shell element. It follows that:

$$\left.\begin{aligned} 2t_s d_r \sigma_c &= \frac{qD_d d_r}{2}\int_0^{\pi}\sin\theta\mathrm{d}\theta \\ t_s &= \frac{qD_d}{2\sigma_c} \end{aligned}\right\} \tag{4}$$

In (4), σ_c is the allowable compressive hoop stress in the material of the drum shell.

Similarly, consider the equilibrium of the rope segment that interacts with the drum shell element that has just been considered. The radial force acting outwards, upon an elemental length of the rope segment may be expressed as:

$$q\mathrm{d}A = \frac{qD_d d_r}{2}\mathrm{d}\theta$$

The vertical component of this force may be expressed as:

$$q\sin\theta\mathrm{d}A = \frac{qD_d d_r}{2}\sin\theta\mathrm{d}\theta$$

Considering the balance of vertical forces acting upon the semi-circular rope segment:

$$\left.\begin{aligned} 2Q &= \frac{qD_d d_r}{2}\int_0^{\pi}\sin\theta\mathrm{d}\theta \\ q &= \frac{2Q}{D_d d_r} \end{aligned}\right\} \tag{5}$$

The result in (5) can also be found in [6]. In (5), Q is the tension in the rope segment and it is assumed to be constant throughout the length of the rope segment. From (4) and (5) it follows that:

$$t_s = \frac{Q}{\sigma_c d_r} \tag{6}$$

Oonishi [7] used the following equation to determine drum shell thickness under the rope:

$$t_s = \frac{Q}{\sigma_c p} \tag{7}$$

In (7), p is the pitch of the rope grooves on the active surface of the drum, as illustrated in Fig. 2.

B. Volume of Material Required to Make the Drum Shell

Consider the active length of the drum shell, which is a right circular cylinder as illustrated in Fig. 3.

The volume occupied by the material of the shell is determined as:

$$V_s = \frac{\pi L}{4}\left(D_o{}^2 - D_i{}^2\right) = \frac{\pi L}{4}\left(D_o + D_i\right)\left(D_o - D_i\right) \tag{8}$$

Now:

$$\frac{D_o - D_i}{2} = t_p \tag{9}$$

In (9), t_p is the thickness of the shell before the rope grooves are machined onto the active surface of the drum.

Referring to Fig. 2, according to [7], shell thickness before machining is determined as:

$$t_p = t_s + \frac{d_r}{2} \tag{10}$$

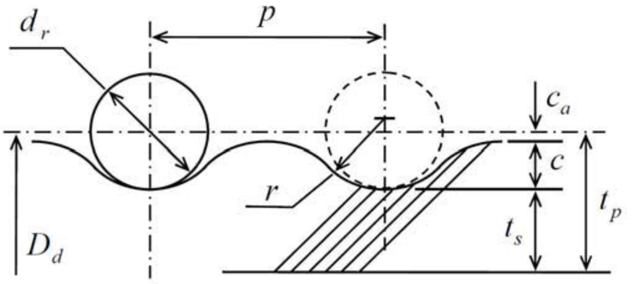

Fig. 2 Drum groove dimensions according to [7]

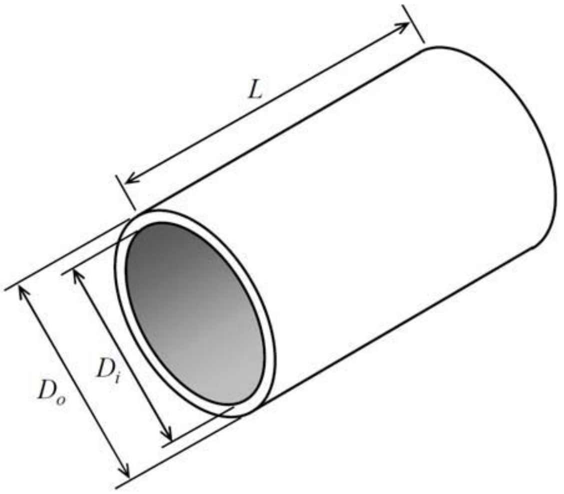

Fig. 3 Right circular cylindrical shell

Since t_s is independent of drum diameter, as was seen in (6), t_p will also be independent of drum diameter. Moreover, (9) and (10) also imply that:

$$D_o = D_d \tag{11}$$

From (9) and (11), it follows that:

$$D_o + D_i = 2(D_d - t_p) \tag{12}$$

Since the length L is the active length of the drum shell, if the total height through which the winch can hoist a load is denoted by h, it follows that:

$$L = \frac{h}{\pi D_d} p \tag{13}$$

Thus:

$$\left.\begin{aligned} V_s &= \frac{\pi}{4}\times\left(\frac{hp}{\pi D_d}\right)\times 2(D_d - t_p)\times 2t_p \\ V_s &= hpt_p\left(1-\frac{t_p}{D_d}\right) \end{aligned}\right\} \tag{14}$$

In (14), for $D_d >> t_p$, the dependence of V_s on D_d is weak and may be neglected. In that case, the following approximation, which slightly exaggerates V_s, may be used:

$$V_s = hpt_p \tag{15}$$

C. Buckling of the Drum Shell

The rope drum shell is a right circular cylinder of relatively small wall thickness. According to Ashby [8] and Timoshenko [9], a thin-walled elastic tube will buckle inwards under the action of a critical value of the external pressure q', given by:

$$q'_{critical} = \frac{3EI}{(r')^3} \tag{16}$$

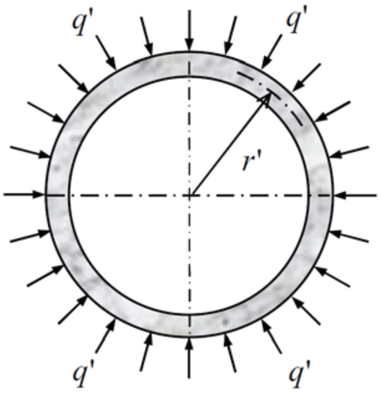

Fig. 4 Drum shell buckling pressure

In Fig 4, q' is lineal pressure measured in Newtons per circumferential metre. If we consider a longitudinal length of drum shell equal to d_r, as illustrated in Fig. 1, then:

$$qd_r = q' \tag{17}$$

Moreover, in (16), I is the second moment of area of a section of the drum shell wall cut parallel to the drum axis (a longitudinal section). If, again, we consider a length of drum shell equal to d_r, then:

$$I = \frac{d_r t_s{}^3}{12} \tag{18}$$

Lastly, in (16), we can estimate r' to be equal to $D_d/2$, which is actually a slightly larger radius and will therefore yield a lower critical buckling load, leading to a more conservative design. Equation (16) can now be re-written as:

$$\left.\begin{aligned} q_{critical} d_r &= 3E \times \frac{d_r t_s^{\ 3}}{12} \times \frac{8}{D_d^{\ 3}} \\ q_{critical} &= \frac{2E t_s^{\ 3}}{D_d^{\ 3}} \end{aligned}\right\} \tag{19}$$

From (5) and (19) the following can be obtained:

$$\left.\begin{aligned} q_{critical} &= \frac{2Q_{critical}}{D_d d_r} = \frac{2E t_s^{\ 3}}{D_d^{\ 3}} \\ Q_{critical} &= \frac{E d_r t_s^{\ 3}}{D_d^{\ 2}} \end{aligned}\right\} \tag{20}$$

In (20), $Q_{critical}$ is the critical tension in the rope which should not be exceeded if buckling of the drum shell is to be avoided.

D. Drum Groove Wear Rate

The number one reason for replacing a rope drum is wear of the grooves [10]. Such wear can make the top surface of the land that separates the grooves to be extremely sharp and capable of cutting the wire rope. Wear in the base of the grooves results in corrugations that prevent the wire rope from twisting and result in pinching and damaging of the rope. Both of these problems can be alleviated through the selection of material and heat treatment of the rope drum.

According to [10], rope drums that are carburized and case hardened to about 60 Rockwell C (654 Brinell 3000 kg) virtually eliminate maintenance on the drum and significantly improve the performance of wire rope.

The relationship between wear rate and the surface hardness of the drum grooves is illustrated in Fig. 5.

It can be seen in Fig. 5 that the following regression equation fits the data closely:

$$\left.\begin{aligned} RWR &= 0.0012RC^2 - 0.1648RC + 6.7961 \\ R^2 &= 0.9994 \end{aligned}\right\} \tag{21}$$

In (21), RWR denotes relative wear rate and RC denotes the Rockwell C hardness number. When the material hardness is stated in terms of the Brinell hardness number then the corresponding equation becomes:

$$\left.\begin{aligned} RWR &= 2394.6BH^{-1.1894} \\ R^2 &= 0.9952 \end{aligned}\right\} \tag{22}$$

In (22), BH denotes the Brinell 3000 kg hardness number.

Some materials that may originally be of low hardness can be case hardened to achieve the required surface hardness. This is often the practice in the design of rope drums.

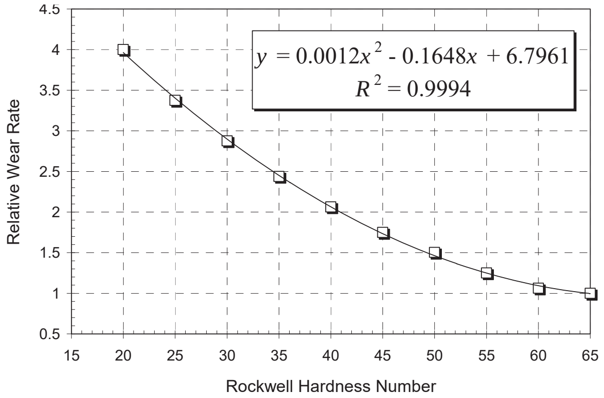

Fig. 5 Drum groove wear rate against groove surface hardness [10]

V. PROCEDURE FOR SELECTING A MATERIAL FOR THE DRUM SHELL

The material selection process will be implemented in three stages, namely Go/No-go screening, ranking of candidate materials by use of indices of merit and use of supporting information to make a final choice of material [3], [11]. Initially, every material that can conceivably be used to make the rope drum should be included as a candidate, provided that adequate relevant information on the material in question is available. Experience may be used, carefully, to guide the inclusion of candidate materials and to avoid the inclusion of those materials that are known to be unsuitable for the application at hand.

A. Go or No-go Screening

Traditionally, wire rope drums have been designed by first considering their ability to withstand the compressive hoop stress that arises in the drum shell [7], [12].

Oonishi [7] used an allowable compressive stress of 65 MPa in designing a cast iron rope drum. Rudenko [12] recommended a permissible compressive stress of 98 MPa for rope drums made of cast iron, 156 MPa for ones that are made of steel castings and 176 MPa for ones that are made of welded steel plates. Butty [13] recommends a maximum allowable compressive hoop stress of 172 MPa, for drum shells, without specifying the material of drum construction.

Materials data documents usually give the materials yield stress σ_y rather than the allowable/permissible stress. If the allowable compressive hoop stress is denoted by σ_c, a safety factor, SF, can be incorporated in the design, which is defined as:

$$SF = \frac{\sigma_y}{\sigma_c} \tag{23}$$

The DNV Standard [14] requires that the calculated compressive hoop stress should not exceed 85% of the material yield stress. This leads to a safety factor of about 1.2. The Australian Standard [15] requires that the calculated compressive hoop stress should not exceed 60% of the material yield stress. This leads to a safety factor of about 1.7.

If the minimum allowable compressive hoop stress, for any material, is set to be 65 MPa and a safety factor of 1.7 is used then the lower limit to the yield stress for any material would be about 111 MPa. This criterion will be used in a Go/No-go screening, such that any material with a yield stress that is lower than 111 MPa will be eliminated. If a material with a yield stress that is higher than 111 MPa should eventually be used to make the drum shell then, for the same safety factor, the allowable compressive hoop stress in the material will be proportionately higher than 65 MPa. This would mean that, for a given load to be hoisted or hauled, a thinner drum shell may be used.

B. Ranking of Candidate Materials by Use of Indices of Merit

Having performed the Go/No-go screening, suppose that there are m candidate materials left, from among which the material to be finally used will be selected. The remaining candidate materials can then be ranked according to their suitability for use in the manufacture of the rope drum, by use of material indices of merit, which can be calculated as:

$$a_i = \sum_{j=1}^{n} b_{ij} c_j \tag{24}$$

In (24):

- a_i is the index of merit for candidate material i,
- b_{ij} is a material performance rating that indicates the extent to which some property or some combination of properties of material i satisfies a design requirement j,
- c_j is a weight that is assigned to design requirement j and is indicative of the relative importance that is attached to design requirement j, as compared to the other design requirements. These weights should be based on the experience and knowledge of the decision maker and their values could be determined by methods such as the Analytic Hierarchy Process or AHP [16], [17].

The scheme of coding of the material performance ratings and the weights assigned to the design requirements should be deliberately and reliably designed, such that the material with the highest index of merit is the one that will give the best overall performance, if used to make the rope drum.

In a mechanical design situation, all the design requirements can be considered to be equally important [4], [18]. In such a case, each of the design requirements should be assigned a weight of unity and (24) would then reduce to:

$$a_i = \sum_{j=1}^{n} b_{ij} \tag{25}$$

After raking the materials by use of the indices of merit, the choice of materials can be narrowed down to only a few top ranked candidates of say five to ten materials. Supporting information can then be used to make the final choice of material.

C. Use of Supporting Information

Supporting information should enable a final choice of the material to be arrived at. The issues to be considered at this stage include the following:

- Case studies on previous designs of similar products. In a process that is known as case-based reasoning (CBR), materials that have been successfully used in similar applications could be regarded favourably, but this alone should not be the basis for a final choice.
- Availability of the candidate materials. If the selected material has to be procured from distant places the eventual cost could rise to prohibitive levels, due to shipping and related charges. Moreover, the procurement of materials from distant places may incur unacceptably long durations of time.
- The purchase price of the candidate materials. Even for those candidate materials that may be available locally, the purchase price could be prohibitively high.
- Manufacturing Processes. It is necessary to consider if the manufacturing processes to be used with each of the candidate materials are available locally and what it would cost to use those processes. Highly specialized manufacturing processes often prove to be costlier.
- Manufacturing Properties. Such factors as casting properties, formability, ease of machining and welding, should be evaluated in the light of the available and the preferred manufacturing processes. For rope drums, in particular, the possibility of case hardening a material to a desired surface hardness is of special interest.
- The forms and sizes in which the materials are available. A material that is available in circular pipe form of adequate diameter and wall thickness, for instance, will facilitate easier and less costly manufacturing of the rope drum. A material that is amenable to fabrication by cutting, forming and joining, and is available in plate form of adequate size and thickness is also suitable for rope drum manufacture.

Although the selection of a material for the manufacture of rope drums has been presented here as if it were a once-through step by step process, in practice some iteration is usually necessary.

VI. TRANSLATING DESIGN REQUIREMENTS INTO MATERIAL PERFORMANCE RATINGS

A. Drum Shell Strength and Mass (Specific Strength)

From (6) and (23), for the drum to be capable of withstanding the compressive hoop stresses that will be developed in its shell, without yielding, the shell thickness under the rope must conform to:

$$t_s > \frac{Q}{\sigma_y d_r} \tag{26}$$

Moreover, from (26) and (10), it follows that:

$$t_p = t_s + \frac{d_r}{2} > \frac{Q}{\sigma_y d_r} + \frac{d_r}{2} \tag{27}$$

Considering (27) and (15), if the mass density of the material is denoted by ρ, the mass of a drum shell that will be of adequate strength can be determined as:

$$m = \rho V_s = \rho hpt_p > \rho hp\left(\frac{Q}{\sigma_y d_r} + \frac{d_r}{2}\right) \tag{28}$$

Khurmi and Gupta [19] give the following relation between the pitch, p, of the grooves on the active drum surface and the diameter, d_r, of the wire rope:

$$p = 1.15 d_r \tag{29}$$

From (28) and (29) it follows that:

$$m > 1.15hQ\left(\frac{\rho}{\sigma_y}\right) + 0.575h\rho {d_r}^2 \tag{30}$$

In (30), it is preferable to select a material of high yield stress σ_y and low density ρ in order to realize a drum of high strength and low mass. From this point of view alone, the material selection process should aim to maximize the following quantity, which may be termed the specific strength:

$$B_1 = \frac{\sigma_y}{\rho} \tag{31}$$

Given the values of B_1 for a number of materials, the specific strength rating b_{i1} for material i will be obtained by dividing the value of B_1 for material i by the median value of B_1 for all the candidate materials.

Dividing B_1 for material i by the median value of B_1 for all the candidate materials expresses the specific strength rating on a scale on which the median value will have a rating of unity. All other values of the rating will then be proportionate multiples of the median value. It also normalizes the specific strength rating, making it dimensionless and therefore not dependent on the units of measure of the material properties that are used in determining the rating. This normalization shall be done for all the material performance ratings.

B. Drum Shell Resistance to Buckling

From (20), the critical rope tension, which if exceeded may cause the drum shell to buckle is given by:

$$Q_{critical} = \frac{E d_r {t_s}^3}{{D_d}^2} \tag{32}$$

From (26) and (32) the critical rope tension can be expressed as:

$$\left.\begin{aligned} Q_{critical} &> \frac{E d_r}{{D_d}^2} \times \frac{Q^3}{{\sigma_y}^3 {d_r}^3} \\ &> \frac{Q^3}{{D_d}^2 {d_r}^2}\left(\frac{E}{{\sigma_y}^3}\right) \end{aligned}\right\} \tag{33}$$

In (33), the actual tension in the rope, which is denoted by Q, has a definite value and it should be less than $Q_{critical}$ in order to avoid buckling of the drum shell. From this point of view alone, the material selection process should aim to maximize the critical rope tension by selecting a material with a high value of the following quantity, which is a measure of the materials resistance to buckling, if used to make the drum shell:

$$B_2 = \frac{E}{{\sigma_y}^3} \tag{34}$$

Given the values of B_2 for a number of materials, the normalized buckling resistance rating b_{i2} for material i will be obtained by dividing the value of B_2 for material i by the median value of B_2 for all the candidate materials.

C. Drum Groove Resistance to Wear

Given either the Rockwell C hardness number or the Brinell hardness number of a material, the relative wear rate of the grooves of a drum that is made of that material can be calculated using either (21) or (22), respectively. Since a material with a low wear rate is desirable, the materials selection process should aim to select a material with a high value of the following quantity, which is a measure of the materials resistance to wear, if used to make the grooved drum shell:

$$B_3 = \frac{1}{RWR} \tag{35}$$

Given the values of B_3 for a number of materials, the normalized wear resistance rating b_{i3} for material i will be obtained by dividing the value of B_3 for material i by the median value of B_3 for all the candidate materials.

D. Affordability

In a given application, the cost of procuring and using a material includes the purchase price of the material, shipping and related charges and the cost of processing the material into the finished product. In the materials selection process, at the stage of ranking candidate materials by use of indices of merit, only the purchase price of the materials shall be considered. Shipping and related charges and the cost of processing the material into the finished product can be considered to be part of the supporting information that will be used to arrive at the final choice of material to be used.

If the purchase price is denoted by P_p, the materials selection process should aim to maximize the following quantity, which is a measure of the materials affordability:

$$B_4 = \frac{1}{P_p} \tag{36}$$

Given the values of B_4 for a number of materials, the normalized affordability rating b_{i4} for material i will be obtained by dividing the value of B_4 for material i by the median value of B_4 for all the candidate materials.

In industrial practice, one can construct and use a materials and material properties database that is as large as the need demands and as the available resources will allow. Here, the intention is to demonstrate a method for the selection of a material in the design of a manual winch rope drum. Because engineering materials are too numerous, the method of materials selection shall be demonstrated by considering only a small subset of metallic materials that can conceivably be used to make a manual winch rope drum. These materials, along with their properties that have a bearing on selecting a material for the rope drum, are presented in Table II, in the appendix.

The materials and the data in Table II were obtained from Appendix B and Appendix C of [20]. The data were counterchecked with those that are presented by [21]-[23], and other online resources.

VII. RESULTS AND DISCUSSION

None of the materials in Table II, in the appendix, had a yield strength that is lower than 111 MPa and therefore none of them were eliminated by the Go or No-go screening process.

A. Ranking of Candidate Materials and Material Categories

Ranking of the candidate materials by use of indices of merit is shown in Table III in the appendix. Moreover, an analysis and comparison of the various material categories, based on performance ratings, is given in Table IV in the appendix. The data in Table IV were used to plot the charts in Figs. 6-10.

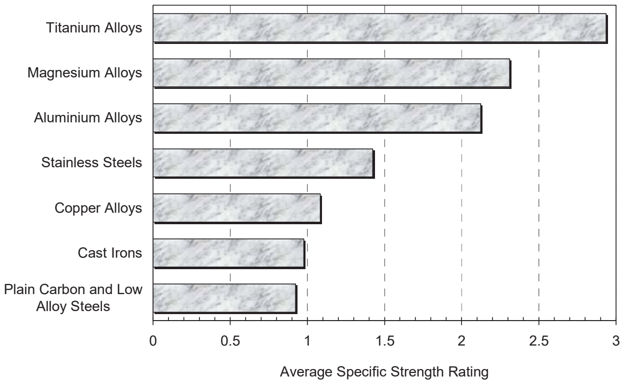

Fig. 6 Comparison of specific strength ratings among the material categories

In Fig. 6, Titanium alloys, Magnesium Alloys and Aluminium Alloys, in that order, have the highest specific strength ratings. This is, to a large extent, because these materials have the lowest densities among the candidate materials. Moreover, Titanium alloys also have high yield strength and this is why they are the highest rated in terms of specific strength. Stainless steels perform moderately in specific strength rating because, even though they have high density, they also have high yield strength. Plain Carbon and Low Alloy Steels are the lowest rated, in terms of specific strength, because they have high density and not-so-high yield strength.

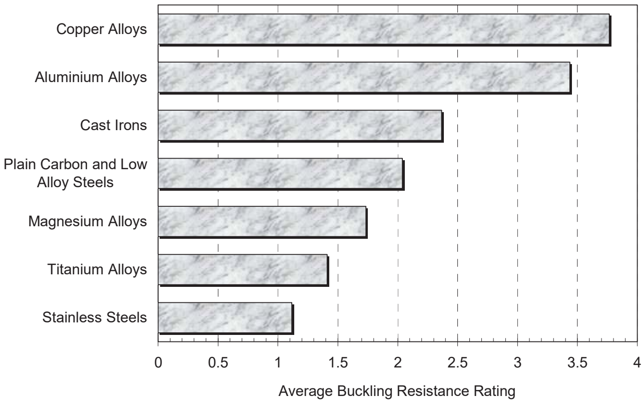

Fig. 7 Comparison of buckling resistance ratings among the material categories

In Fig. 7, Copper Alloys, Aluminium Alloys and Cast Irons, in that order, have the highest buckling resistance ratings. In general, materials that have a high modulus of elasticity, combined with low or moderate yield strength would have a high buckling resistance rating. Plain Carbon and Low Alloy Steels perform moderately in terms of buckling resistance. Stainless Steels and Titanium Alloys generally have high yield strength and, consequently, they are the lowest rated in terms of buckling resistance.

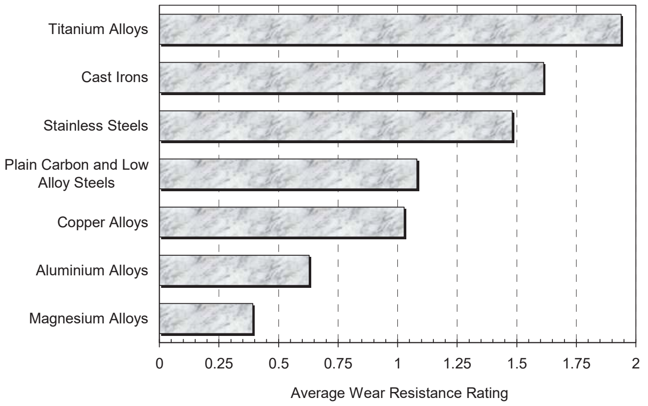

Fig. 8 Comparison of wear resistance ratings among the material categories

In Fig. 8, Titanium Alloys and Cast Irons have the highest wear resistance ratings. Wear resistance is solely determined by the materials hardness and therefore the materials with the highest hardness numbers have the highest wear resistance ratings. Once again, Plain Carbon and Low Alloy Steels perform moderately in terms of wear resistance. Magnesium and Aluminium Alloys have the lowest wear resistance ratings because they have generally low hardness numbers.

Wear resistance is particularly important in the design of wire rope drums because, as stated earlier, the number one reason for replacing a rope drum is wear of the grooves [10]. However, before summarily dismissing materials of low hardness for their low wear resistance, the possibility of case hardening in some materials in order to realize the required surface hardness should be considered.

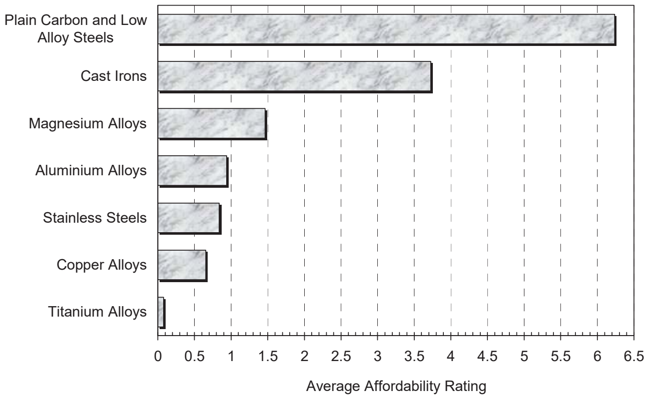

Fig. 9 Comparison of affordability ratings among the material categories

In Fig. 9, Plain Carbon and Low Alloy Steels have the highest affordability rating while Titanium Alloys have the lowest rating. In calculating the affordability ratings, only the relative cost of the materials was used. In practice, the availability of the material and the cost of processing the material into the finished product need to be taken into account, but these can be considered as supporting information when making the final choice of material.

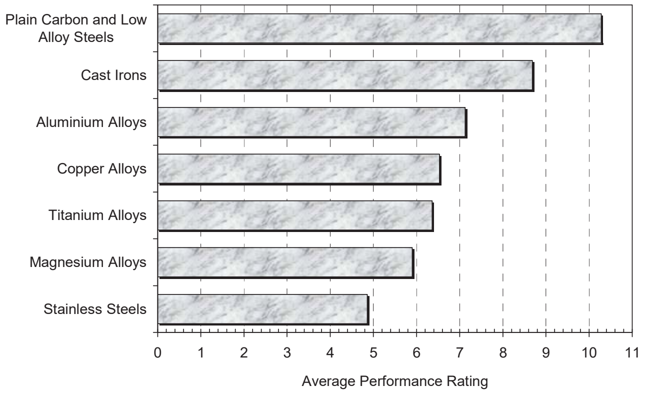

Fig. 10 Comparison of indices of merit among the material categories

In Fig. 10, Plain Carbon and Low Alloy Steels have the highest index of merit, among the candidate categories of materials, followed by Cast Irons. Rudenko [12] stated that drums for use with steel wire rope are made of cast iron, steel castings or steel weldments. According to [24], their Tool Steel Process (TSP) rope drums are manufactured from low carbon steel, which is carburized and hardened to produce a longer lasting rope drum.

Even though only a small sample of metallic materials was used to demonstrate the materials selection process, the findings are in agreement with current industry practice. In an endeavour to reach a final choice of material for the manufacture of the rope drum, focus can be directed at Plain Carbon and Low Alloy Steels as well as Cast Irons, and then available supporting information can be used to reach a final decision.

B. Supporting Information

In using supporting information to arrive at a final choice of material, the result depends, to a large extent, on the prevailing circumstances in a given locality. Therefore, only that information which is generally applicable shall be invoked here.

The top five ranked materials in Table III are reproduced in Table I. Though the top ranked material in this table is a gray cast iron, three of the remaining materials are plain carbon and low alloy steels. The only other material among the top five is a copper alloy. Both the copper alloy and the gray cast iron have buckling resistance ratings that are substantially higher than those of the plain carbon and low alloy steels. This can be explained by the higher yield strength of the steels, as compared to both the gray cast iron and the copper alloy.

During operation, the rope drum actually sustains compressive hoop stresses, amongst other loading. Therefore, in the design of the rope drum, it is the compressive strength of the material that should be of greater concern, rather than the tensile strength. However, in calculating the buckling resistance ratings, it is the tensile yield strength that was used. This is alright for most metallic materials, whose tensile and compressive strengths happen to be about equal, yet for gray cast irons, the compressive strength is generally about three times the value of the tensile strength, as can be seen in Fig.

11, in the Appendix, which was plotted using data obtained from ASM [25]. If, for gray cast iron, the compressive strength is used to calculate the buckling resistance ratings, as should be the case, the Index of Merit for F10004 Gray Cast Iron will be about 7 (Normalized Index of Merit will be about 1) which is much lower than that of the steels in Table I. Moreover, casting as a production process is suitable for mass produced components, which the rope drum is not. Therefore, in the manufacture of rope drums, Plain Carbon and Low Alloy Steels are to be preferred to gray cast iron.

As for the copper alloy C71500, its performance as a rope drum material is inferior to the steels in every respect except buckling resistance. Moreover, two of the steels in Table I have a higher Index of Merit than the copper alloy and the last steel in the table has only a slightly lower Index of Merit than the copper alloy. The copper alloy also has by far the lowest affordability rating in Table I and affordability is always an important factor in product design.

In addition to the above considerations, plain carbon and low alloy steels are generally readily available, they can be easily fabricated and they can possibly be carburized to obtain the desired high surface hardness of the rope drum. Therefore, a plain carbon or low alloy steel that can be carburized should be preferred for the manufacture of the manual winch rope drum.

TABLE I
THE TOP FIVE RANKED CANDIDATE MATERIALS

Rank	Material	UNS Number	Specific Strength Rating	Buckling Resistance Rating	Wear Resistance Rating	Affordability Rating	Index of Merit	Normalized Index of Merit
1	Gray Iron Grade G1800	F10004	0.379	8.444	1.305	4.027	14.156	2.085
2	Steel Alloy 1040	G10400	0.824	1.677	0.996	9.781	13.278	1.956
3	Steel Alloy 1020	G10200	0.597	4.416	0.702	6.847	12.561	1.850
4	Copper-Nickel 30%	C71500	0.349	10.799	0.475	0.326	11.950	1.760
5	Steel Alloy A36	K02600	0.668	3.151	0.762	6.847	11.428	1.683

VIII. CONCLUSION

Equations to be used in the mechanical design of a manual winch rope drum were used to obtain four material performance ratings that should be considered in selecting a material for a manual winch rope drum. These ratings were then used to calculate indices of merit for a sample of thirty-two metallic materials. The candidate materials were then ranked according to their indices of merit and it was found that a plain carbon or low alloy steel that can be carburized should be preferred for the manufacture of the manual winch rope drum.

Although only a small sample of metallic materials was used for candidate materials, the results of the material selection process are in agreement with current industry practice. However, the results would inspire more confidence if a larger and more varied sample of candidate materials were used in the selection process, provided that the relevant materials properties data are available. It is particularly challenging to obtain reliable materials cost data for use in the selection process.

The materials selection process that has been developed and demonstrated here can possibly be adapted and used in the selection of materials for the manufacture of other mechanical components.

APPENDIX

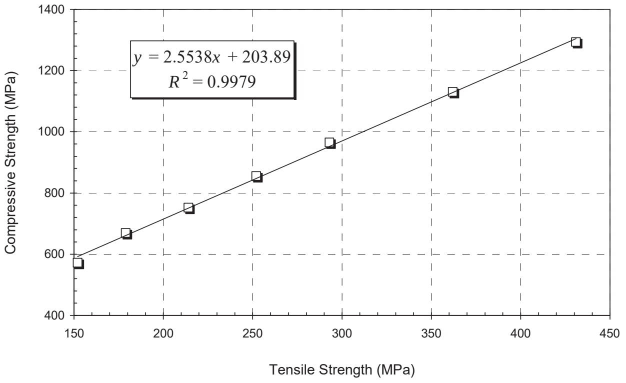

Fig. 11 Compressive strength versus tensile strength for some gray cast irons

TABLE II
CANDIDATE MATERIALS FOR ROPE DRUM MANUFACTURE

Material Category	Material	UNS Number	Form	Density (kg/m^3)	Elastic Modulus (GPa)	Yield Strength (MPa)	Brinell Hardness Number	Relative Cost
Plain Carbon and Low Alloy Steels	Alloy A36	K02600	Plate	7850	207	235	119	1.0
	Alloy 1020	G10200	Hot rolled plate	7850	207	210	111	1.0
	Alloy 1040	G10400	Hot rolled plate	7850	207	290	149	0.7
	Alloy 4140	G41400	Annealed plate	7850	207	417	197	1.6
	Alloy 4340	G43400	Annealed plate	7850	207	472	217	2.0
Stainless Steels	Alloy 304	S30400	Hot finished and annealed plate	8000	193	290	143	6.0
	Alloy 316	S31600	Hot finished and annealed plate	8000	193	290	143	7.6
	Alloy 405	S40500	Annealed plate	7800	200	276	150	58.57
	Alloy 440A	S44002	Annealed plate	7800	200	415	209	6.7
	Alloy 17-7PH	S17700	Cold rolled plate	7650	204	1210	378	7.1
Cast Irons	Gray Iron G1800	F10004	As cast	7300	81.5	124	187	1.7
	Gray Iron G3000	F10006	As cast	7300	101.5	207	214	1.7
	Gray Iron G4000	F10008	As cast	7300	124	276	243	1.7
	Ductile Iron 60-40-18	F32800	Annealed	7100	169	276	167	2.0
	Ductile Iron 80-55-06	F33800	As cast	7100	168	379	192	2.0
	Ductile Iron 120-90-02	F36200	Oil quenched and tempered	7100	164	621	331	2.0
Aluminium Alloys	Aluminium Alloy 1100	A91100	H14 Plate	2710	69	117	32	4.2
	Aluminium Alloy 2024	A92024	T351 Plate	2780	73	290	120	13.4
	Aluminium Alloy 6061	A96061	T651 Plate	2700	69	276	120	5.0
	Aluminium Alloy 7075	A97075	T6 Plate	2800	71	503	150	10.0
	Aluminium Alloy 356.0	A03560	Sand cast	2690	72.4	125	75	13.6
Copper Alloys	ETP Copper	C11000	H04 Cold worked	8890	115	310	95	7.4
	Beryllium Copper	C17200	TH04 Plate	8250	128	1150	350	17.5
	Cartridge Brass	C26000	H04 Plate	8530	110	435	154	7.5
	Free-cutting Brass	C36000	H02 Hollow bar	8500	97	310	143	7.0
	Copper-Nickel 30%	C71500	M20 Plate	8940	150	140	80	21.0
	Bearing Bronze	C93200	Sand cast	8930	100	125	65	17.9
Magnesium Alloys	Alloy AZ31B	M11311	Rolled plate	1770	45	220	73	23.4
	Alloy AZ91D	M11916	As cast	1810	45	150	63	2.6
Titanium Alloys	ASTM Grade 1	R50250	Annealed plate	4510	103	170	120	85.6
	Alloy Ti-5Al-2.5Sn	R54520	Annealed plate	4480	110	760	320	89.3
	Alloy Ti-6Al-4V	R56400	Annealed plate	4430	114	830	331	94.2

TABLE III
RANKING OF CANDIDATE MATERIALS BY USE OF INDICES OF MERIT

Rank	Material	UNS Number	Specific Strength Rating	Buckling Resistance Rating	Wear Resistance Rating	Affordability Rating	Index of Merit	Normalized Index of Merit
1	Gray Iron Grade G1800	F10004	0.379	8.444	1.305	4.027	14.156	2.085
2	Steel Alloy 1040	G10400	0.824	1.677	0.996	9.781	13.278	1.956
3	Steel Alloy 1020	G10200	0.597	4.416	0.702	6.847	12.561	1.850
4	Copper-Nickel 30%	C71500	0.349	10.799	0.475	0.326	11.950	1.760
5	Steel Alloy A36	K02600	0.668	3.151	0.762	6.847	11.428	1.683
6	Aluminium Alloy 1100	A91100	0.963	8.511	0.160	1.630	11.264	1.659
7	Bearing Bronze	C93200	0.312	10.115	0.371	0.382	11.181	1.647
8	Aluminium Alloy 356.0	A03560	1.037	7.323	0.440	0.503	9.303	1.370
9	Gray Iron Grade G3000	F10006	0.633	2.261	1.532	4.027	8.453	1.245
10	Ductile Iron Grade 120-90-02	F36200	1.951	0.135	2.574	3.423	8.084	1.191
11	Gray Iron Grade G4000	F10008	0.844	1.165	1.782	4.027	7.818	1.152
12	Stainless Alloy 17-7PH	S17700	3.529	0.023	3.014	0.964	7.530	1.109
13	Magnesium Alloy AZ91D	M11916	1.849	2.634	0.358	2.633	7.474	1.101
14	Steel Alloy 4140	G41400	1.185	0.564	1.388	4.279	7.417	1.093
15	Ductile Iron Grade 60-40-18	F32800	0.867	1.588	1.141	3.423	7.019	1.034
16	Titanium Alloy Ti-6Al-4V	R56400	4.180	0.039	2.574	0.073	6.866	1.011
17	Steel Alloy 4340	G43400	1.342	0.389	1.558	3.423	6.711	0.989
18	Ductile Iron Grade 80-55-06	F33800	1.191	0.610	1.347	3.423	6.571	0.968
19	Titanium Alloy Ti-5Al-2.5Sn	R54520	3.785	0.050	2.472	0.077	6.383	0.940
20	Beryllium-Copper	C17200	3.110	0.017	2.750	0.391	6.268	0.923
21	ASTM Grade 1 Titanium	R50250	0.841	4.142	0.770	0.080	5.833	0.859
22	Aluminium Alloy 7075	A97075	4.008	0.110	1.004	0.685	5.807	0.855
23	Aluminium Alloy 6061	A96061	2.281	0.648	0.770	1.369	5.068	0.747
24	Stainless Alloy 304	S30400	0.809	1.563	0.949	1.141	4.462	0.657
25	Magnesium Alloy AZ31B	M11311	2.773	0.835	0.426	0.293	4.327	0.637
26	Stainless Alloy 316	S31600	0.809	1.563	0.949	0.938	4.258	0.627
27	Stainless Alloy 440A	S44002	1.187	0.553	1.490	1.022	4.251	0.626
28	Aluminium Alloy 2024	A92024	2.327	0.591	0.770	0.511	4.200	0.619
29	Stainless Alloy 405	S40500	0.789	1.879	1.004	0.117	3.790	0.558
30	Free-Cutting Brass	C36000	0.814	0.643	0.949	0.978	3.384	0.498
31	Cartridge Brass	C26000	1.138	0.264	1.036	0.913	3.351	0.494
32	Electrolytic Tough Pitch Copper	C11000	0.778	0.763	0.583	0.925	3.049	0.449

TABLE IV
COMPARISON OF MATERIAL CATEGORIES BY USE OF PERFORMANCE RATINGS AND INDICES OF MERIT

Material Category	Average Specific Strength Rating	Average Buckling Resistance Rating	Average Wear Resistance Rating	Average Affordability Rating	Average Index of Merit
Plain Carbon and Low Alloy Steels	0.923	2.039	1.081	6.235	10.279
Stainless Steels	1.425	1.116	1.481	0.836	4.858
Cast Irons	0.977	2.367	1.613	3.725	8.683
Aluminium Alloys	2.123	3.437	0.629	0.940	7.128
Copper Alloys	1.084	3.767	1.027	0.653	6.530
Magnesium Alloys	2.311	1.734	0.392	1.463	5.901
Titanium Alloys	2.935	1.410	1.939	0.076	6.361

REFERENCES

[1] Jahan, Ali and Kevin L. Edwards, *Multi-criteria decision analysis for supporting the selection of engineering materials in product design*. Elsevier, 2013.

[2] Athawale, V. M. and S. Chakraborty, “Material selection using multiple criteria decision making methods: A Comparative Study,” *Proceedings of the Institution of Mechanical Engineers Part L, Journal of Materials: Design and Applications*, 226(4), pp 266-285, 2012.

[3] Ashby, M. F., Y. J. M. Brechet, D. Cebon and L. Salvo, “Selection strategies for materials and processes,” *Materials and Design*, 25, pp 51-67, 2004.

[4] Oduori, M. F. and T. O. Mbuya, “Wire rope selection for manual winch application,” *Journal of Engineering, Design and Technology*, Volume 7, Number 2, 2009.

[5] Dimarogonas Andrew D., *Computer aided machine design*. Prentice Hall International, 1989.

[6] Budynas, G. R. and J. K. Nisbett, *Shigley’s mechanical engineering design, ninth edition in SI units*. McGraw-Hill International, 2011.

[7] Oonishi, K., *Modern machine design practice 1 – design of the manual winch and the electric overhead traveling (EOT) crane (in Japanese)*. Ohm Sha, Tokyo, 1988.

[8] Ashby, M. F., *Materials selection in mechanical design, third edition*. Elsevier Butterworth Heinemann, 2005.

[9] Timoshenko, Stephen P., *Strength of materials part 2: advanced theory and problems, third edition*. CBS Publishers and Distributors, New Delhi, India, 2002.

[10] Xtek, “Rope drums.” http://www.xtek.com/rope-drums.htm (accessed in August 2007).

[11] Cebon D. and M. F. Ashby, "The optimal selection of engineering entities." *Technical Report CUED/C-EDC/TR* 59, November 1997, ISSN 0963-5432. Cambridge University Engineering Department. http://www-mech.eng.cam.ac.uk/cms/publ/papers/gen3.pdf (accessed in January 2013).

[12] Rudenko, N., *Material handling equipment, first indian edition*. Envee Publishers, New Delhi, 1978.

[13] Butty, Julius, "Drum hoists rules of thumb," *Hard Rock Miner's Handbook*. McIntosh Engineering, North Bay Ontario, Canada. www.mne.eng.psu.ac.th/pdf/HRMH3.pdf (accessed in January 2013).

[14] Det Norske Veritas AS, *Standard for certification No. 2.22: lifting appliances*. http://exchange.dnv.com/publishing/stdcert/Standard2-22.pdf (accessed in January 2013).

[15] Lim Buan Teck, Danny, *Improvement in the design of winches*." Report Submitted in Partial Fulfillment of the Requirements for the Award of the Degree of Bachelor of Engineering of the National University of Singapore. http://dynamicslab.mpe.nus.edu.sg/dynamics/project0405/thesis0405/Improvement%20of%20design%20of%20winches.pdf (accessed in January 2013).

[16] Saaty, T. L., "How to make a decision: the analytic hierarchy process," *European Journal of Operational Research*, 48, 9-26, 1990. http://www.ida.liu.se/~TDDD06/literature/saaty.pdf (accessed in December 2013).

[17] Taha, H. A., *Operations research-an introduction, 8th edition*. Prentice-Hall of India, 2008.

[18] Oduori, M. F., "Application of decision theory and information processing in the selection of engineering entities," in *Proceedings of the Twentieth International Conference on Materials Handling, Construction and Logistics,* held at the Faculty of Mechanical Engineering, The University of Belgrade, Belgrade, Serbia, 3rd – 5th October 2012.

[19] Khurmi, R. S. and J. K. Gupta, *A textbook of machine design*. Eurasia Publishing House (PVT) Ltd, New Delhi, 2005.

[20] Callister, W. D. and D. G. Rethwisch, *Fundamentals of materials science and engineering: an integrated approach, third edition*. John Wiley and Sons Incorporated, 2008.

[21] Smith, W. F. and J. Hashemi, *Foundations of materials science and engineering, fifth edition: materials properties database*. McGraw-Hill Higher Education, 2010. http://highered.mcgraw-hill.com/sites/0073529249/student_view0/properties_database.html (accessed in December 2013)

[22] www.matweb.com

[23] www.azom.com

[24] Xtek, "Rope drum brochure." http://www.xtek.com/pdf/ropedrum-brochure.pdf (accessed in December 2013).

[25] ASM, *ASM handbook, volume 1: properties and selection: iron, steels and high-performance alloys, pages 12 to 32: gray iron*. ASM International, 1990.