Drive System Selection in Lightweight Design of a Portable Core Drill: A Group Decision Making Approach

J. Taylor, J. Parisien, W. Truman, M. Saunders, A.S. Milani*, A. Jahan, J. Seabrook

***Abstract*— Complexity of selecting a lightweight design, which is needed for many engineering machines, can be increased by multiplicity of, often conflicting, design criteria. This case study presents an example of such a case in design of a man portable top drive unit that is required to drill core samples. The top drive unit of the portable drill consists of a drive box and a chuck system. For the drive box, a multiple criteria decision making (MCDM) process is employed to determine the best drive system among belt, chain and gear options. The drive box requires taking the input from the motor using an SAE C mount, and transferring it to the output shaft. Attached to the output shaft is the chuck that grips the pipe during drilling operation. A hydraulic cylinder is employed to enable the chuck to release and grip the pipe with the application of the hydraulics. A finite element analysis of the drive box has been implemented to verify its safety factor during operation.**

***Index Terms*— Drive system selection, Finite element analysis, Multicriteria decision-making, Portable core drill.**

I. Introduction

Nowadays, companies are faced with the challenge of capturing fast-moving targets in developing new products. A key driver of market is the rapidly increasing demand by customers for better product performance and lower cost, which often contributes to ambiguity on the success of a new product. Therefore, modern manufacturers are continually challenged to find ways to improve their products by exploring new optimization-driven design alternatives.

Diamond core drilling is historically used to take cylindrical samples (core) of soil from earth's depth and bring to surface, e.g., for geological studies. Samples from the core drill are usually taken at several different depths during the operation to better understand the earths' composition at a given geographical location. Core drilling is today becoming a large emerging industry, in particular due to the inaccessibility of certain geological sites where lightweight mobile drills must be set up and used. In the 1980's, top drive drilling units essentially took over the core drilling market in most offshore areas of the world [1]. The top drive units that came to the market were designed to replace the power swivels of the past. A main reason for the change was to improve the total time of drilling operation, and also more efficient pipe handling. In essence, three main efficiencies expected from such machines include 'drilling', 'rod handling', and 'transportation and setup'. Although there is an ongoing development towards fully hydraulic/electric drilling rigs, mechanical rigs (often combined by hydraulic/electric sub-components) are still of widespread use, owing to their ease of maintenance for applications in remote areas [2]. However, the weight of each sub-component plays a vital role as part of the system's overall efficiency and, hence, weight reduction is a challenge and state-of-the-art in the related manufacturing sectors.

Over the past few decades, multi-criteria decision-making (MCDM) techniques have been applied in diverse engineering applications, demonstrating significant capability for tackling complex design problems (e.g., [3]-[6]). Following similar techniques, the present case study is to show how multi-criteria subsystem selection m be employed in optimizing a sub-component of a top drive drilling system. Section 2, describes the portable core drill under consideration, design process and the MCDM approach applied for the drive system selection. Section 3 includes results of the MCDM, followed by a discussion on verification of drive box load-bearing capacity through finite element analysis (FEA). Section 4 includes a summary of the main findings.

II. Case study: Lightweight portable core drill

A. Description of overall design

The portable core drill under consideration (Figure 1) was originally designed and reported by Taylor et al. [7]. During the development of the top drive unit, several important design considerations have been assumed: The unit will be designed so that four people are able to carry it into remote areas and retrieve core samples. The system will be mounted on a platform that includes ergonomic handles for transport. Once the unit is carried to the remote location, the top drive will be mounted to the motor, along with other modules. When the top drive is operational it will be able to be used in periodic drilling applications. This is because, when operational, the drill will be cycling between the feed/torque cycle, and the pullback cycle. It will also have some downtime when the new section of drill pipe is added. The drill must be human operated and also satisfy the numeric design specifications in Table 1.

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Table 1: Portable core drill performance specifications (numeric constraints)

Maximum Weight (including lubrication)	440	Lbs
Torque	3000	ft-lbs
Drive Ratio	1:2	
Power	150	HP
Speed of High Gear	2500	RPM
Speed of Low Gear	1250	RPM
Pullback Force	30,000	Lbs
Feed Force	16,000	Lbs
Bit Weight	13,000	Lbs

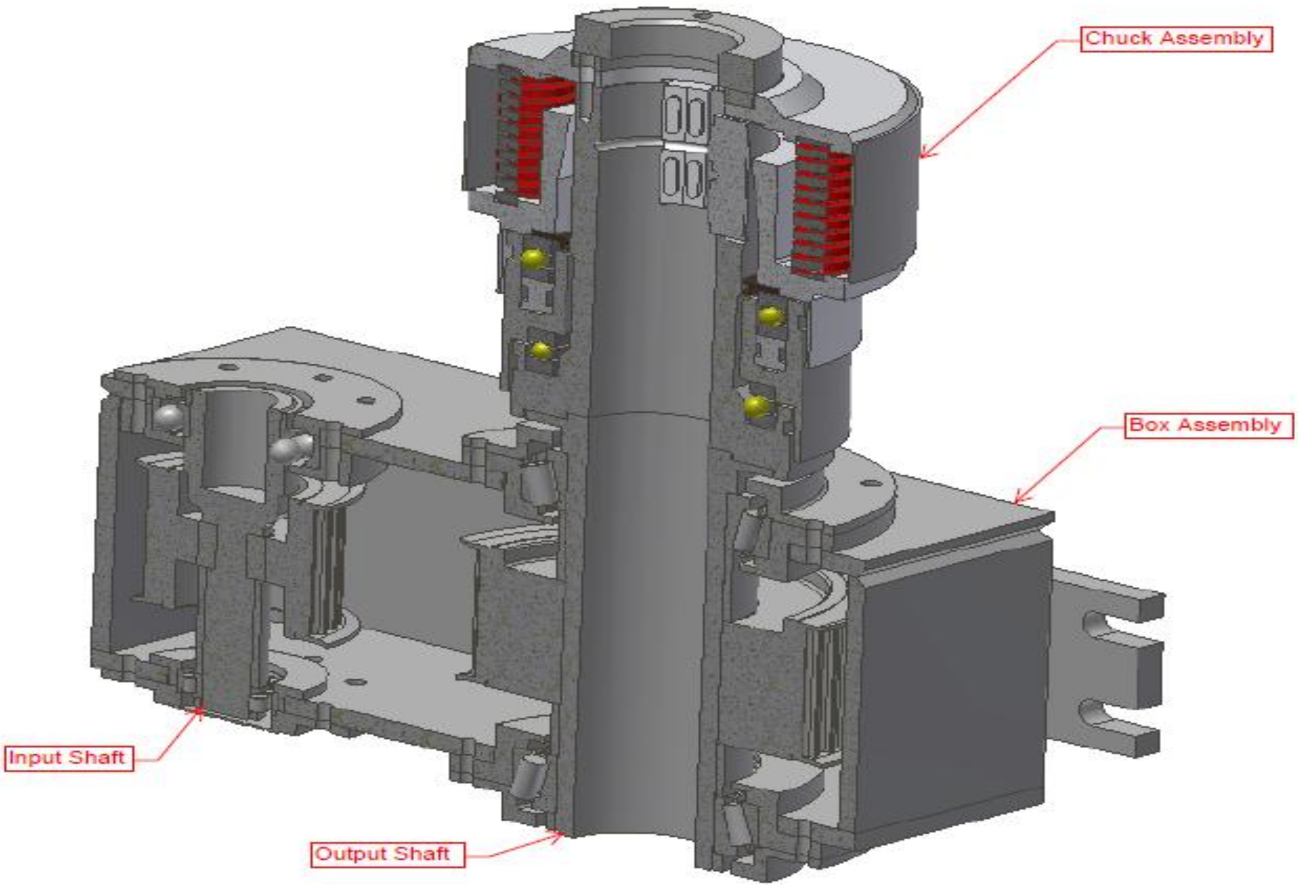

Figure 1: Section view of the top-drive assembly [7]

Additionally, the pinion shaft must mate with an ANSI 44-4 shaft through a SAE C mount. The mount must be a female connection in order for the motor to connect to the system. The top drive will consist of two key systems, a chuck and a drive box (Figure 1). During drilling operation, the main function of the chuck is to grip the pipe so that torque is transmitted from the motor to the pipe. The chuck is required to hold the entire weight of the drill bit and be able to apply an additional pullback force in case the bit gets stuck. The drive box, in turn, is tasked with transferring the force of the motor to the chuck. The drive box consists of a pinion (input) shaft and a drive (output) shaft as shown in Figure 1.

B. MCDM methodology for drive box/sub-system selection

Three possible options (alternatives) for the drive system were considered: gears drive, chain drive, or belt drive. To choose the best alternative, it has long been recognized that customer requirement analysis is one of the most crucial activities for the success of product development and it creates an expectation for what the design should be. Translating customer requirements into appropriate technical requirements helps a company in designing quality into the product in early stages of design [8]. After consulting with potential customers in this study, five important criteria were selected as cost, weight, size, required maintenance, and life. To solve the ensuing MCDM problem (i.e., ranking the available options for the drive system given the multiple criteria), VIKOR and extended TOPSIS methods [9] were employed. VIKOR, which is a 'multi-criteria optimization and compromise solution method', was earlier discussed by Opricovic & Tzeng [10]. The method has been developed to solve specific types of MCDM problems when the decision-

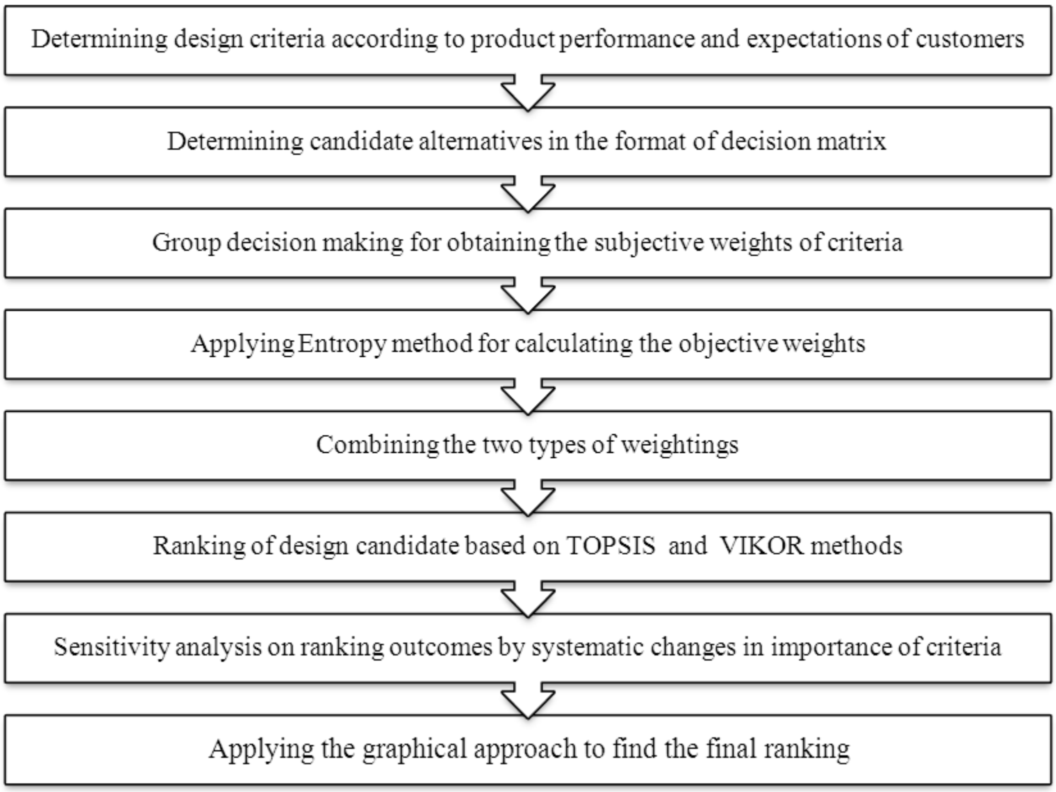

Figure 2: The MCDM stages applied to the drive system selection problem

makers seek a compromise solution that is the closest to an ideal solution. TOPSIS technique, which enjoys a wide acceptance today in the MCDM field, is based on the principle that the optimal option should have the shortest distance from the positive ideal solution and the farthest from the negative ideal solution. In both of these methods relative importance weights over criteria can be assigned objectively (i.e., via statistical measures of the given data in decision matrix) or subjectively (i.e., via direct input of the decision makers). Objective and subjective weights can also be combined systematically [11] in order to (1) evaluate effect of weighting methods on the final ranks, and (2) find the ultimate ranking based on the frequency of sub-ranks. Figure 2 summarizes the applied MCDM steps.

III. RESULTS AND DISCUSSION

As stated earlier, in the drive system selection, five criteria including cost, weight, size, maintenance requirement, and life were employed. Among these criteria only "life" should be maximized and for the other four criteria, smaller values are preferable. For the cost and weight, ordinal data were considered (based on the 10-point scale in Table 2) since their exact numeric values would be very difficult to obtain at early stages of design, e.g., due to final variations in machining specifications, etc. The criterion ‘maintenance required’ considers the difficulty, frequency and time estimated for maintenance. Table 3 shows subjective weights through direct weighting of a group of decision makers over the five decision criteria, considering overall design requirements/goals outlined in Section 2 .1. Each member of the group was tasked to judge the importance of each criterion as a percentage, and then geometric means were used for the final aggregation of weights.

Table 2: 10-point scale used for evaluating ordinal criteria (Yoon & Hwang 1995)

Extremely Low	0
Very Low	1
Low	3
Average	5
Above Average	7
Very High	9
Extremely High	10

In addition to the subjective weights in Table 3, the entropy method [12] was employed with the deduced decision matrix of Table 4 to determine a set of objective weighting as shown in Table 5. In order to check the sensitivity of ranking over the design criteria, combined weights were obtained using Equation (1); where w_j^o , and w_j^s are the objective are subjective weightings, and $0 \le \lambda \le 1$.Table 6 shows details of all the weights.

$$W_j = w_j^s \lambda + w_j^o (1-\lambda) \qquad j = 1, 2, 3, \ldots, n \qquad (1)$$

Table 3: Subjective weighting of criteria by a group of decision makers

Decision Maker	Cost (%)	Mass (%)	Size (%)	Maintenance Required (%)	Life (%)
1	25	30	15	15	15
2	15	30	30	10	15
3	20	40	10	15	15
4	10	50	15	15	10
Geometric means	16.55	36.63	16.12	13.55	13.55
Subjective weights	0.17	0.38	0.17	0.14	0.14

Table 4: Decision matrix for the drive system selection [7]

	Criteria				
	Relative Cost	**Relative Mass**	**Size (in)**	**Maintenance Required**	**Life**
Data type	Ordinal data	Ordinal data	Numeric	Ratio values	Related to #of extracted cores
Objective type	Min.	Min.	Min.	Min.	Max.
Gears	7	9	9.750	1	80
Belt	3	5	18.958	1.6	41
Chain	5	8	18.958	2	62

Table 5: Objective weighting by Entropy method

Selection criteria	**Cost**	**Mass**	**Size**	**Maintenance Required**	**Life**
E_j	0.950	0.974	0.963	0.966	0.968
w_j^o	0.28	0.14	0.21	0.19	0.18

Table 6: Combining weights under uncertainty in importance of each weighting type

Selection criteria and weighting	**Cost**	**Mass**	**Size**	**Maintenance Required**	**Life**
Subjective weighting (w_j^s)	0.17	0.38	0.17	0.14	0.14
Objective weighting (w_j^o)	0.28	0.14	0.21	0.19	0.18
Combined weights for monitoring the sensitivity of ranking to λ					
w (λ=0)	0.28	0.14	0.21	0.19	0.18
w (λ=0.4)	0.24	0.24	0.19	0.17	0.16
w (λ=0.8)	0.19	0.33	0.18	0.15	0.15
w (λ=1)	0.17	0.38	0.17	0.14	0.14

Table 7: Ranking of drive systems by extended TOPSIS and VIKOR methods under different weightings

Candidate Systems	Different MCDM methods with different λ values of 0, 0.4,0.8, and 1 under each															
	TOPSIS				VIKOR ($\nu = 0.3$)				VIKOR ($\nu = 0.5$)				VIKOR ($\nu = 0.7$)			
	0	0.4	0.8	1	0	0.4	0.8	1	0	0.4	0.8	1	0	0.4	0.8	1
Gears	2	2	2	2	3	3	3	3	3	3	3	3	2	2	2	2
Belt	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Chain	3	3	3	3	2	2	2	2	2	2	2	2	3	3	3	3

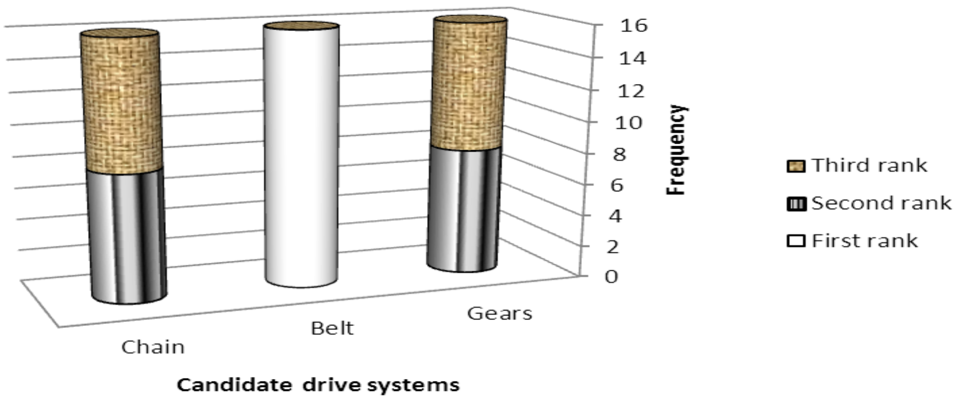

Figure 3: Distribution of ranks for the drive systems based on different ranking and weighting methods

Table 7 demonstrates the ranking of designs using extended TOPSIS method. Based on the results obtained, the belt system ranked higher than the chain and gear options, under all uncertainty factors of λ. Also as a second confirmation, Table 7 demonstrates ranking orders of candidate systems by VIKOR method with different values of *v*. It is observed that, the belt system remains the best choice for the three tested values of *v*, although the relative ranking of chain and gear systems changes. Figure 3 shows distribution of ranks for drive systems and stability of the top rank design over the two ranking methods and different values of λ.

A. Drive box FEA

The drive box houses all of the drive components as well as the bearings and seats. The pullback and feed forces from the chuck are transmitted to the box though the angular contact bearings. Essentially, it was necessary to run an FEA using the pullback force, but not the feed force. This is because the pullback force is much larger than the feed force, and both the top and bottom plate are identical in shape, size and materials. Per Table 1, the 30,000 lbs pullback force was applied to the top bearing seat which was constrained to the box. The back wall of the box was fixed, assuming that it is the rigid part of the structure. The resulting stresses are seen in Figure 4. The maximum effective stress revealing from this FEA was approximately 60% of the yield strength of the box material (steel, ~345 MPa), rendering a high safety factor.

IV. Conclusions

In a world where new materials and mechanical components are constantly being developed with enhanced properties, there are high demand for substituting the traditional ones. For heavy duty portable core drills, an optimization-driven design approach presented in this work may provide an opportunity for improving the overall performance (wright, size, cost, life, maintenance requirement) of top-drives. The complete design can also include the optimization of the chuck, drive assembly, and input and output shafts of the drill (Taylor et al. 2013). A typical portable drill module would have an assembled weight of roughly 450lbs. By optimally varying design parameters such as dimensions and material as well as appropriate sub-component selection (such as drive box system), this weight can be reduced. For the drive box, an optimal driver system was realized using a group multiple criteria decision making (MCDM) technique in the present work, and it was found to be a belt-driven system. Furthermore, the finite element analysis was employed to evaluate the rating of the design; where a safety factor of ~1.6 for the maximum effective stress in the drop box material was obtained.

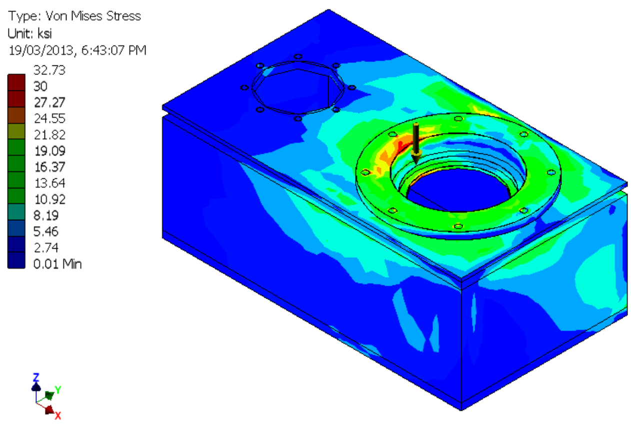

Figure 4: Finite element (static) analysis of the drive box

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