

Causal vs. Non-Causal Selection of Onshore Environmentally Friendly Drilling Systems

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Abstract

A significant number of drilling technologies have been developed by the petroleum industry to reduce the environmental impact during oil and gas drilling operations. However, these technologies have not been fully integrated into a decision-making system capable of combining existing and new technologies into an optimal and Environmentally Friendly Drilling (EFD) system for a given site. This paper introduces two quantitative decision methods (causal vs. non-causal) for selecting a system for a specific site when applied to a case study in Green Lake at McFaddin, TX. The purpose is to show the differences between the selection systems based on a causal and a non-causal approach. Results of a comparative analysis show a natural trend towards the incorporation of causality as part of the system selection process. In this way, a causal approach will provide a more rational way to help decision-makers select an optimal and EFD system for a given site.

1. Introduction

One of the petroleum industry's goals is to minimize the environmental impact during drilling operations since an effective management of the environment has proven to lead greater access of potential reserves in environmentally sensitive areas that are currently off-limits (Rogers *et al.*, 2006). In order to reduce the environmental impact during drilling operations, a number of Environmentally Friendly Drilling (EFD) technologies have been developed to varying degrees but few have been integrated into a decision-making system that combines current and new EFD technologies into an optimal drilling system for a specific site.

As part of an initial effort, Yu et al. (2009) developed an evaluation protocol to incorporate a number of current and emerging EFD technologies into a single and clean drilling system, aiming at reducing environmental impact. The objective of their approach was to help decision-makers select an optimal drilling system for a specific site by minimizing the environmental impact and maximizing profit at the same time.

In this paper, two different drilling system selection methods, causal and non-causal, are introduced to show the different selection of EFD systems. In order to compare the proposed systems, a case study was conducted for Green Lake at McFaddin, TX. The result comparison analysis shows the importance of causal dependencies between system components during the search of an optimal solution.

2. Drilling system selection procedure

This section briefly summarizes the optimal drilling system selection procedure developed by Yu et al. (2009). A quantitative technology evaluation protocol was proposed to select an optimal drilling system for a given site. Within the proposed system selection method, four main subsystems and thirteen subsets have been identified for the EFD operations as shown in Figure 1. This Figure shows one example of a possible drilling system, and it is required to evaluate all possible systems to find the optimal drilling system for a given site.

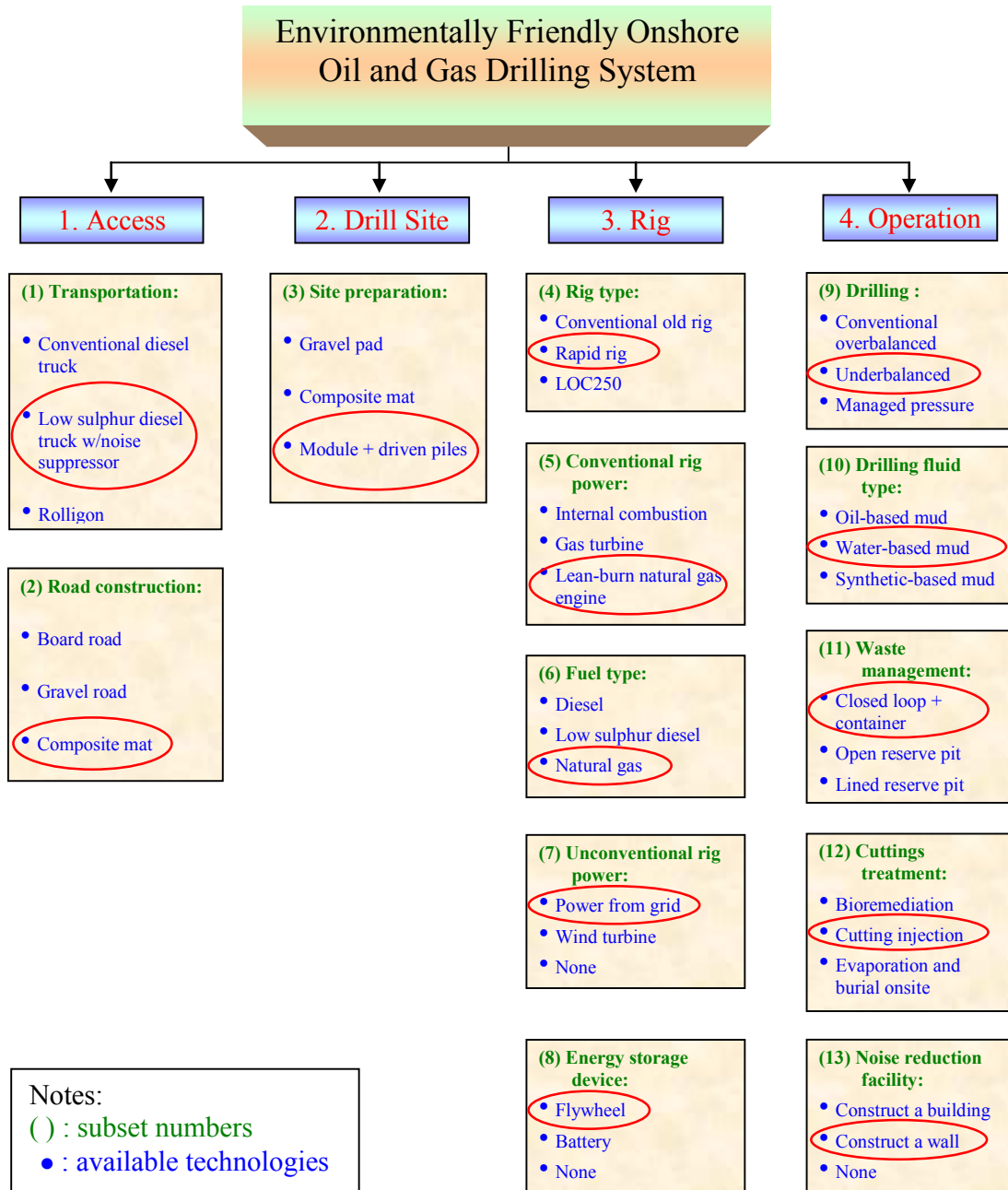


Figure 1. An example of the EFD technology selection

An attribute is one of the parameters considered in the evaluation of the system (e.g., cost, land area, emission, perception, and safety). In order to evaluate available technologies for drilling projects against each attribute, attribute scales that explicitly described their possible impacts on a project need to be specified (Keeney and Raiffa, 1976).. Nine attributes are defined for the EFD system as shown in Figure 2.

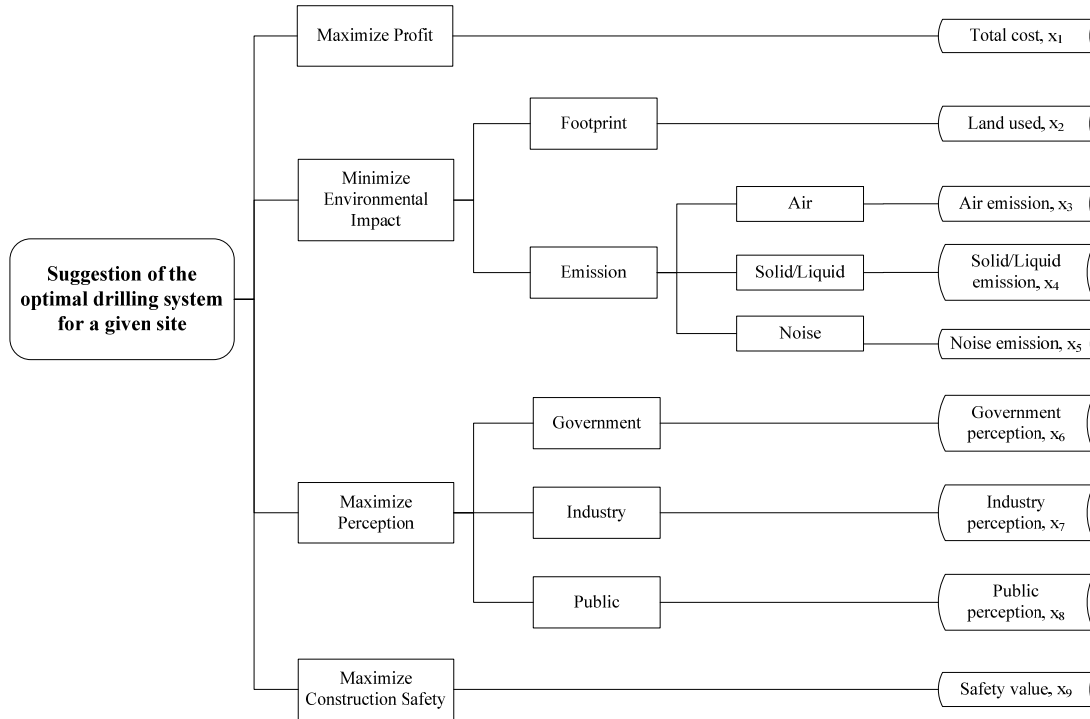


Figure 2. Fundamental objectives hierarchy and attributes for the EFD project

After each technology is evaluated in terms of the attributes (i.e., x_1 through x_9), for each attribute, the overall attribute score of a system is calculated by adding the technology scores of the system or selecting the minimum technology score of the system. Figure 3 shows the overall attribute score for each attribute of a system. It is noted that attribute scores are not evaluated for the empty cells because those attribute scores are not relevant to the particular subsets or already included in technologies within other subsets. As can be seen in Figure 3, the overall scores of cost (x_1), footprint (x_2), and emissions (x_3 through x_5) are calculated by summing the scores of technologies selected within each subset. The overall scores of perceptions (x_6 through x_8), and safety (x_9), however, are calculated by choosing the worst score among technologies selected within each subset for a system because it is suggested that perception and safety values should be considered on the systems level not on the individual technology level.

Once the overall attribute score for each attribute of a system is calculated in terms of the nine attributes (i.e., x_1 through x_9), for each of these, and in order to homogenize the scores, a utility function (u_i) needs to be developed to convert the overall dimensional score of a system into a non-dimensional utility value of the system (between 0 and 1). Figure 4 shows an example of utility function curves used in this study. As can be seen in Figure 4, the maximum and the minimum values of each attribute need to be obtained in order to generate the utility function curves.

Selected Technologies in Each Subset	Weights ($\Sigma = 100\%$ \therefore O.K!)								
	40%	25%	5%	5%	5%	5%	5%	5%	5%
	Total Cost (\$)	Ecological Footprint (Acres)	Emissions			Perceptions			Safety Value
		Air	Solid & Liquid	Noise (TWA)	Gov.	Ind.	Public		
(1) Transportation: Conventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: Composite Mat (rent)	\$132,000	1.515	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: Composite Mat (rent)	\$90,000	1.033	0.976		79.945	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	\$182,000		0.977		77.458	1.000	0.500	1.000	1.000
(5) Rig power (Conventional): Internal combustion engine w/SCR, w/noise suppressor	\$73,369		0.574		90.259	0.750	0.750	0.750	0.750
(6) Fuel type: Low sulphur diesel	\$47,628					0.750	0.750	1.000	0.750
(7) Rig power (Unconventional): Electric power from grid (10 %)	\$5,918	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: Flywheels	\$30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling tech.: Conventional overbalanced drilling	\$170,000				115.385	1.000	0.500	0.500	0.500
(10) Fluid type: Water-based muds	\$47,940					1.000	1.000	1.000	1.000
(11) Waste mgmt.: Closed loop + containers + solid control equip.*	\$30,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings mgmt.: Cuttings injection	\$54,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction facility: N/A									
Overall Attribute Scores (Σ or minimum value)	\$862,855	2.548	4.490	2.000	445.917	0.250	0.500	0.250	0.500
Single Attribute Utility Values	0.883	0.764	0.757	1.000	0.655	0.250	0.500	0.250	0.500

\therefore Multi-Attribute Utility Value = 0.740

Figure 3. An example of a system matrix

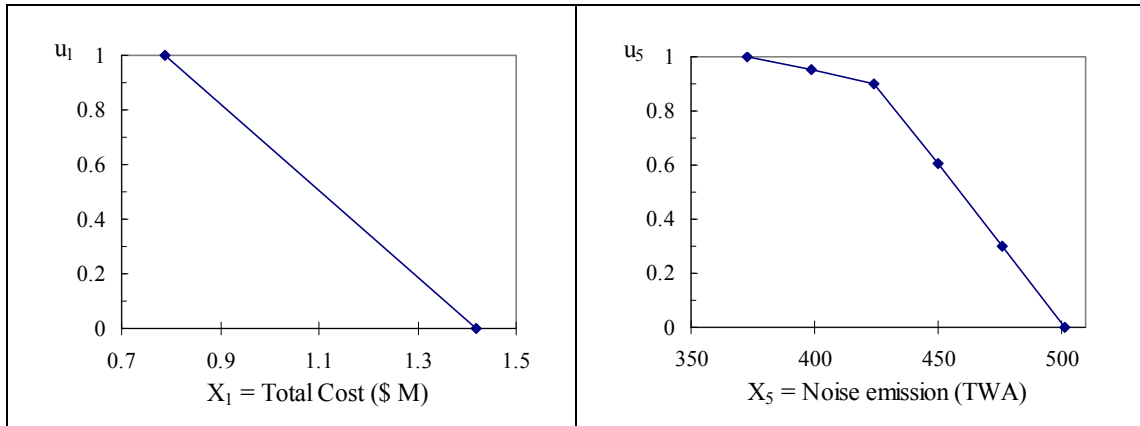


Figure 4. The single-attribute utility function curves

Since it is assumed that there is no interaction between each attribute, all of the weights are positive and they must sum to one (Hardaker, 2004). One weight combination example assigned to a system is shown in Figure 3. If mutual preferential and utility independence are satisfied, it is possible to define the multi-attribute utility function with the additive form (Keeney and Raiffa, 1976):

$$\begin{aligned}
 U(X_1, X_2, \dots, X_I) &= U\{u_1(X_1), u_2(X_2), \dots, u_I(X_I)\} \\
 &= k_1 u_1(X_1) + \dots + k_I u_I(X_I) = \sum_{i=1}^I k_i u_i(X_i)
 \end{aligned}
 \tag{1}$$

where $u_i(X_i)$ is a single-attribute utility function scaled from 0 to 1, k_i is a weight factor for $u_i(X_i)$.

Since exhaustive search optimization is a simple, practical and very robust method given the speed of modern computers (Cover *et al.*, 2007), it is used to evaluate all possible systems and to find the ‘best’ available system that should be particularly attractive for a specific site. After the optimization scheme has given the ‘best’ system, it is suggested to conduct a sensitivity analysis to examine the impact of possible changes in the attribute scores, weight factors, and utility functions on the best system. For example, the weight assigned to the cost attribute shown in Figure 3 could be changed from the initially assigned value of 0.40. Since the weighting factors must sum to one in this study, the weights assigned to other attributes are known once a weight assigned to the cost attribute is decided. Note that the final answer needs not be a single system but that a few “optimal” systems which come close to best score can be selected. This may provide some flexibility for the person in charge of the drilling process.

3. Web-based applications

A web-based decision optimization tool (Non-causal) was developed to follow the drilling system selection process and then select an optimal system for a given site. This application was used by students, who took ‘Drilling Engineering (PETE661)’ class at Texas A&M University, for their well site design term project in the spring semester of 2008 and 2009. Recently a new version of the application (Causal) has been developed to take into account the causal dependencies between the system components during the best system selection process. The key features of both applications are summarized in Table 1.

Table 1. Key features of two web-based decision optimization tools

Features	Non-causal	Causal
Provide a quantitative basis for selecting EFD drilling systems	O	O
Evaluate different EFD drilling technologies	O	O
Optimize selection of EFD systems for given conditions	O	O
Introduce drilling time variation effects	X	O
Introduce causal dependencies between the system components	X	O
Geo-references	X	X
Risk-based EFD system selection	X	X
Documentation	X	X

In this section, we introduce the differences between the proposed methods and compare the results. In order to compare the optimal drilling systems, a case study was conducted for Green Lake at McFaddin, TX. Results show the importance of causal dependencies between system components during the search of an optimal solution, as it is discussed below.

3.1 Web-based application (Non-causal).

This web-based application helps users follow the drilling system selection process and then select an optimal system for a given site. The influence diagram considered in this application is shown in Figure 5. This Figure shows a drilling system consisting of thirteen subsets (one technology within each subset) and few dependencies between subsets are taken into account when selecting an optimal drilling system. Since this application does not consider causal dependencies between each subset, we just fixed the total drilling days (i.e., 16 days) and then calculated total cost. Other attribute values of each technology were also evaluated independently.

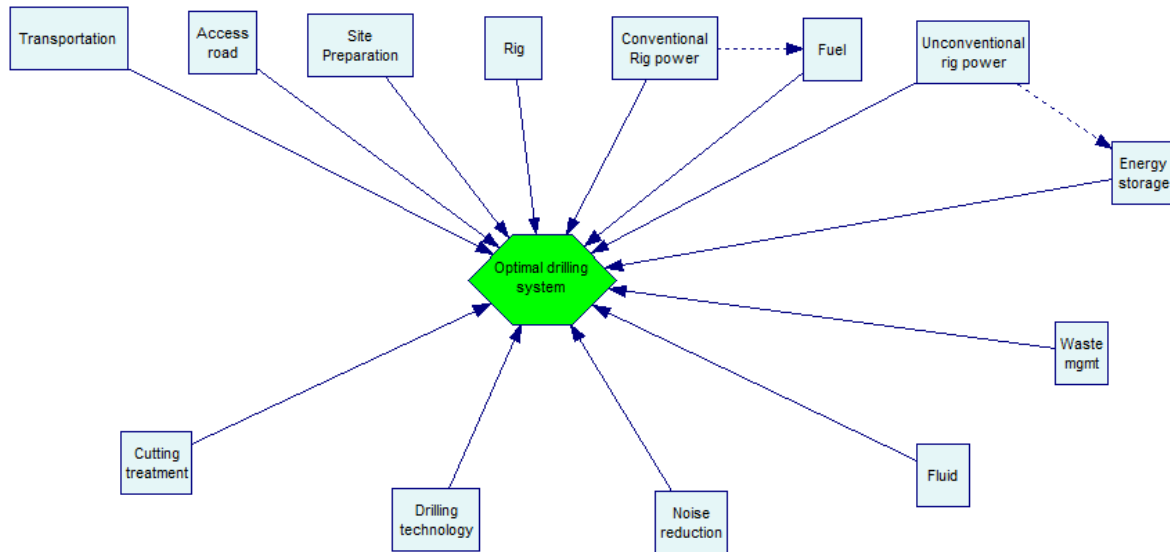


Figure 5. Influence diagram considered in the application (Non-causal)

3.2 Web-based application (Causal).

This application considers causal dependencies between each subset and thus each attribute score is varied by some of the influence variables such as total drilling time. In order to take into account causal dependencies between system components, it is necessary to develop a well defined influence diagram for drilling system. The influence diagram for the drilling site was developed through a series of meetings with EFD experts and it is presented in Figure 6. This diagram should be considered before estimating attribute scores of technologies because attribute scores of a technology can be dependent on key influence variables such as drilling time and rig type. Different rig type causes the variation of total drilling time (i.e., 11 ~ 16 days) and the total drilling time varies total cost of technologies within many subsets. For example, it is necessary to consider different total cost for the same technology within 'Conventional rig power' subset according to a selected rig type because each rig type has its own drilling speed and thus total drilling time should be varied by the selected rig type. The total cost of the same technology within 'Access road' subset also varies by a selected transportation type because it is sure that the mobilization cost of a technology within 'Access road' subset

increases as a more expensive transportation type is selected. Moreover, the total footprint of the same technology within ‘Site preparation’ subset varies by a selected rig type because each rig type uses different land area. The relevance of taking into account the effect of causality as part of the system selection is illustrated in the case study below.

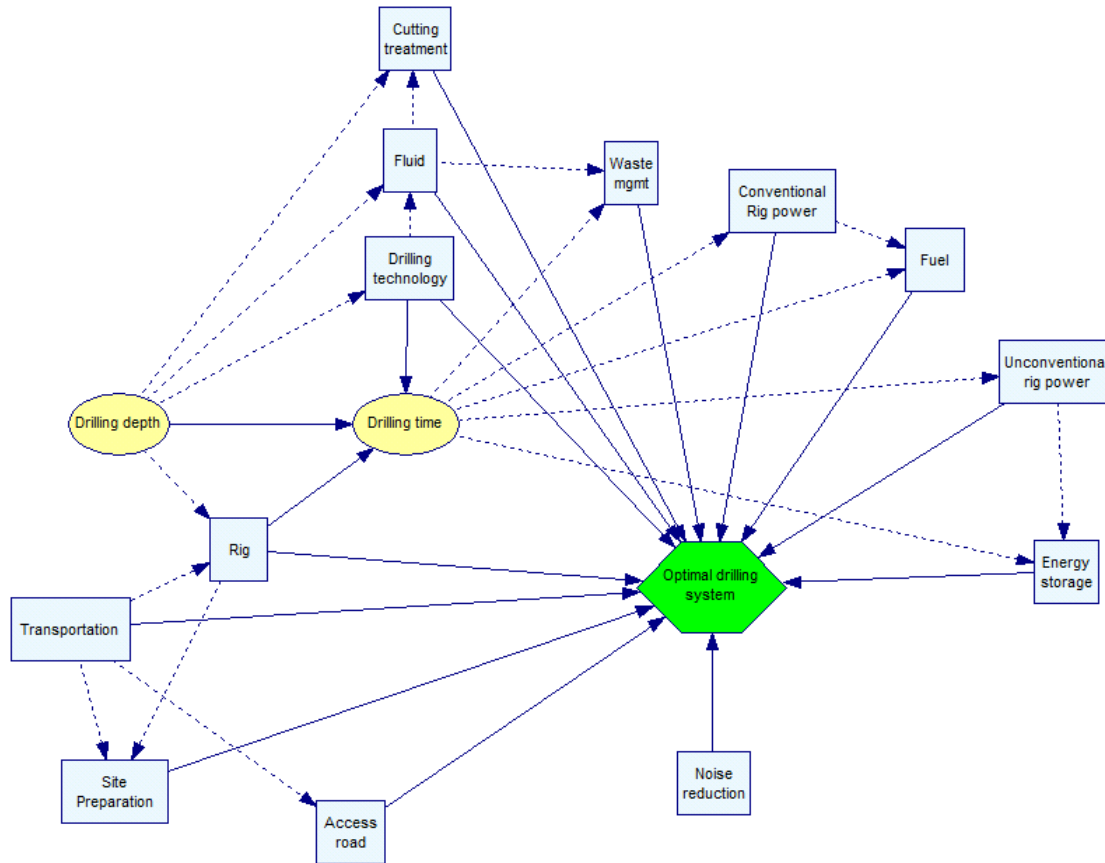


Figure 6. Influence diagram considered in the application (Causal)

3.3 Result comparisons.

The base-case weight combination is defined as shown in Table 2 to compare the optimal drilling systems selected by both applications (Non-causal and Causal) at the same condition. Table 3 and Table 4 give an example of the best systems of varying the weight on the cost attribute from zero to one in Non-causal and Causal. Since the weights must sum to one, as one weight increases, others must decrease. For example, as the weight assigned to the cost attribute increases, the weights assigned to other attributes decrease by the ratio of the base-case weight combination given in Table 2. Since Underbalanced Drilling (UBD) and Managed pressure drilling (MPD) methods can reduce a system’s total cost due to the decreased drilling time comparing to Conventional Overbalanced Drilling (COBD) method, UBD or MPD are mainly selected as an optimal drilling system’s component in Causal tool. In Non-causal tool, however, once the weight factor of the cost attribute is greater than 33%, COBD is selected as an optimal drilling system’s component because COBD’s daily cost is cheaper than UBD and MPD’s daily cost.

Table 2. Base-case weight combination

Attributes	Weights
Total cost (x_1)	0.40
Footprint (x_2)	0.20
Air emission (x_3)	0.20/3
Solid/ liquid emission (x_4)	0.20/3
Noise emission (x_5)	0.20/3
Government perception (x_6)	0.05
Industry perception (x_7)	0.05
Public perception (x_8)	0.05
Safety (x_9)	0.05

Table 3. Optimal systems as varying the weight on the cost attribute in Non-causal tool

Subsets No.	SeT 1 ($0\% \leq w_1 < 20\%$)	SeT 2 ($20\% \leq w_1 < 33\%$)
(1)	Low sulphur diesel truck w/noise suppressor	Low sulphur diesel truck w/noise suppressor
(2)	Composite Mat (rent)	Composite Mat (rent)
(3)	Aluminum modules + driven piles	Composite Mat (rent)
(4)	Rapid Rig	Rapid Rig
(5)	Lean-burn natural gas engines w/noise suppressor	Lean-burn natural gas engines w/noise suppressor
(6)	Natural gas	Natural gas
(7)	Electric power from grid (10%)	Electric power from grid (10%)
(8)	Flywheel	Flywheel
(9)	Managed pressure drilling w/noise suppressor	Underbalanced drilling w/noise suppressor
(10)	Water-based muds	Water-based muds
(11)	Closed loop + containers + solid control equipment	Closed loop + containers + solid control equipment
(12)	Cuttings injection	Cuttings injection
(13)	None	None
Subsets No.	SeT 3 ($33\% \leq w_1 < 64\%$)	SeT 4 ($64\% \leq w_1 \leq 100\%$)
(1)	Conventional diesel truck	Conventional diesel truck
(2)	Composite Mat (rent)	Composite Mat (rent)
(3)	Composite Mat (rent)	Composite Mat (rent)
(4)	Conventional older rig	Conventional older rig
(5)	Lean-burn natural gas engines w/noise suppressor	Internal combustion engine
(6)	Natural gas	Conventional diesel
(7)	None	None
(8)	None	None
(9)	Conventional overbalanced drilling	Conventional overbalanced drilling
(10)	Water-based muds	Water-based muds
(11)	Closed loop + containers + solid control equipment	Lined reserve pit + solid control equipment
(12)	Cuttings injection	Cuttings injection
(13)	None	None

Table 4. Optimal systems as varying the weight on the cost attribute (w_1) in Causal tool

Subsets No.	SeT 1 ($0\% \leq w_1 < 2\%$)	SeT 2 ($2\% \leq w_1 < 27\%$)	SeT 3 ($27\% \leq w_1 < 48\%$)
(1)	Low sulphur diesel truck w/noise suppressor	Low sulphur diesel truck w/noise suppressor	Low sulphur diesel truck w/noise suppressor
(2)	Composite Mat (rent)	Composite Mat (rent)	Composite Mat (rent)
(3)	Aluminum modules + driven piles	Aluminum modules + driven piles	Composite Mat (rent)
(4)	LOC250 (CWD)	LOC250 (CWD)	LOC250 (CWD)
(5)	Lean-burn natural gas engines w/noise suppressor	Lean-burn natural gas engines w/noise suppressor	Lean-burn natural gas engines w/noise suppressor
(6)	Natural gas	Natural gas	Natural gas
(7)	Electric power from grid (30%)	Electric power from grid (10%)	Electric power from grid (10%)
(8)	Flywheel	Flywheel	Flywheel
(9)	Managed pressure drilling w/noise suppressor	Managed pressure drilling w/noise suppressor	Underbalanced drilling w/noise suppressor
(10)	Water-based muds	Water-based muds	Water-based muds
(11)	Closed loop + containers + solid control equipment	Closed loop + containers + solid control equipment	Closed loop + containers + solid control equipment
(12)	Cuttings injection	Cuttings injection	Cuttings injection
(13)	None	None	None
Subsets No.	SeT 4 ($48\% \leq w_1 < 81\%$)	SeT 5 ($81\% \leq w_1 \leq 100\%$)	
(1)	Conventional diesel truck	Conventional diesel truck	
(2)	Composite Mat (rent)	Composite Mat (rent)	
(3)	Composite Mat (rent)	Composite Mat (rent)	
(4)	LOC250 (CWD)	LOC250 (CWD)	
(5)	Lean-burn natural gas engines w/noise suppressor	Internal combustion engine	
(6)	Natural gas	Conventional diesel	
(7)	None	None	
(8)	None	None	
(9)	Underbalanced drilling w/noise suppressor	Underbalanced drilling w/noise suppressor	
(10)	Water-based muds	Water-based muds	
(11)	Closed loop + containers + solid control equipment	Lined reserve pit + solid control equipment	
(12)	Cuttings injection	Cuttings injection	
(13)	None	None	

As can be seen in Table 4, SeT 3 is preferred over SeT 2 as the weight assigned to the cost attribute increases and SeT 1, containing 30% of unconventional power usage, is only selected as the optimal system when the cost attribute has a very low weight ($w_1 < 2\%$). This is simply because currently developed unconventional power generation

methods and energy storage devices are costly even though they significantly decrease emission rates. Moreover, 'conventional diesel truck' is selected for subset (1) rather than 'low sulphur diesel truck with noise suppressor' when the weight assigned to the cost attribute is greater than 48% because 'conventional diesel truck' is cheaper than 'low sulphur diesel truck with noise suppressor'.

In summary, LOC 250, UBD, and MPD, which can reduce the total drilling time (cost), footprint, and emissions, are most likely to be selected as optimal drilling system's components when following the Causal approach. It is reasonable to state that if one technology can cause to reduce other components' cost, footprint, and emissions, it can be selected as an optimal drilling system's component even if its daily cost is more expensive than other alternatives. The Causal approach takes into account this kind of dependencies between each drilling component, as opposed to just reflect the exhaustive search of optimal technologies (i.e., less expensive conventional technologies) in the non-Causal approach.

4. Conclusion

Throughout this paper, two different drilling system selection methods are introduced based on a combination of multi-attribute utility theory and exhaustive search optimization. The system selection methodologies used in this paper are designed to help decision-makers with their choices of EFD technology in onshore drilling operations. A causal approach provides a more rational and transparent decision-making process to help decision-makers select an optimal drilling system for a specific site by giving higher relevance to the environmental impact and to the maximization of profit.

In conclusion, the technology selection process for a drilling project is mainly based on managerial experience, but a more logical approach based on systems analysis is possible, and additional research based on causal risk principles could improve the current system selection tools. Even though the technology selection process can be computationally burdensome, it can be very helpful to decision-makers in refining their decisions on a more scientific basis.

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References

- Clemen, R.T. & Reilly, T., 2001. *Making Hard Decisions with DecisionTools*: Duxbury, Pacific Grove, CA.
- Cover, K.S., Verbunt, J.P.A., De Munck, J.C. & Van Dijk, B.W., 2007. Fitting a single equivalent current dipole model to MEG data with exhaustive search optimization is a simple, practical and very robust method given the speed of modern computers. *International Congress Series*, 1300, 121-124.
- Crawford, D.M., Huntzinger, B.C. & Kirkwood, C.W., 1978. Multiobjective decision analysis for transmission conductor selection. *Management Science*, 24, 1700-1709.
- Dyke, K.V., 1997. *Fundamentals of Petroleum*, Fourth ed. Austin, TX: Petroleum Extension Service.
- Guikema, S. & Milke, M., 1999. Quantitative decision tools for conservation programme planning: Practice, theory and potential. *Environmental Conservation*, 26, 179-189.
- Guikema, S.D. & Milke, M.W., 2003. Sensitivity analysis for multi-attribute project selection problems. *Civil Engineering and Environmental Systems*, 20, 143-162.
- Hardaker, J.B., 2004. *Coping with Risk in Agriculture*: CABI Publishing, Cambridge, MA.
- Hovorka, S.D., Doughty, C., Knox, P.R., Green, C.T., Pruess, K. & Benson, S.M., 2001. Evaluation of brine-bearing sands of the Frio formation, upper Texas Gulf Coast for geological sequestration of CO₂. *First National Conference on Carbon Sequestration*. Washington, DC, May 14-17.
- Insua, D.R., 1990. *Sensitivity Analysis in Multi-objective Decision Making*: Springer-Verlag, New York, NY.
- Keeney, R.L., 1992. *Value-Focused Thinking: A Path to Creative Decisionmaking*: Harvard University Press, Cambridge, MA.
- Keeney, R.L. & Raiffa, H., 1976. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*: Cambridge University Press, New York, NY.
- Medina-Cetina, Z., Feinmberg, J. & Nadim, F., 2008. Probabilistic Threshold Definition of Early Warning Systems to Natural Hazards. *33rd International Geological Congress*. Oslo, Norway, August 6-14.
- Onwubolu, G.C. & Clerc, M., 2004. Optimal path for automated drilling operations by a new heuristic approach using particle swarm optimization. *International Journal of Production Research*, 42, 473-491.
- Rehm, B., Schubert, J., Haghshenas, A., Paknejad, A. & Hughes, J., 2008. *Managed Pressure Drilling*: Gulf Publishing Company, Houston, TX.
- Rogers, J.D., Knoll, B., Haut, R., Mcdole, B. & Deskins, G., 2006. *Assessments of Technologies for Environmentally Friendly Drilling Project: Land-Based Operations*. Texas A&M University Environmentally Friendly Drilling report.
- Yu, O.-Y., Briaud, J.-L., Guikema, S. & Hann, R., 2009. Systems Approach and Quantitative Decision Tools for Technology Selection in Environmentally Friendly Drilling. Ph.D. Dissertation, Texas A&M University.