Integrated approach for the optimal selection of environmentally friendly drilling systems

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Abstract

There is a pressing need in the energy industry to develop technologies capable of reducing the environmental impact during oil and gas drilling operations. However, these technologies have not been fully integrated into a decision-making system that can reflect a quantitative effort toward this goal. This paper introduces two quantitative decision methods for the selection of environmentally friendly drilling systems. One is based on a multi-attribute utility approach and the other one is based on the analysis of interventions or causal approach. To illustrate the applicability of the proposed methods and to contract their benefits and limitations, a case study is presented using data collected from Green Lake at McFaddin, TX, USA.

Keywords: Comparative analysis, Environmentally friendly drilling, Decision-making, Multi-attribute utility, System selection, Intervention, Causal approach

Background

One of the current goals of the oil and gas industry is to minimize the environmental impact during drilling operations. This is because an effective management of the environmental impacts during drilling operation has proven to lead to a greater access of reserves in environmentally sensitive areas, particularly those classified as 'off-limits' [1-3]. As a consequence, a significant number of Environmentally Friendly Drilling (EFD) technologies continue to emerge, but these have not been integrated into a decision-making method capable of combining them to define an optimal drilling system for specific conditions on a given site. In practice, the major challenge is to select the best combination of EFD technologies based on a set of competing evaluation criteria. In this paper, a 'system' will be defined as a set of EFD technologies.

From an engineering perspective, the civil infrastructure needed to complete a drilling operation may strongly condition its success (e.g., access and maintenance of roads, power supply, water availability and management of residuals, traffic and noise control). This interaction is exacerbated when the drilling operations expand on large areas, and at a rapid pace, threatening the sustainability of the inherent civil infrastructure.

A number of studies have introduced decision support systems for the selection of drilling well locations [4-7]. A few studies on the best practices on the use of EFD technologies are also available such as in the case of drilling waste discharge [8] and in the design of cementing [1]. However, to the best knowledge of the authors, there are few precedents on a quantitative decision-making method for the integral selection of standard drilling systems.

This work aims at introducing a decision-making evaluation protocol to find the optimal EFD system for a given drilling site and also discusses the sensitivity of the inherent input parameters with respect to the expected outcomes. A search algorithm is proposed as the basis of a multi-attribute utility model combined with an exhaustive enumeration of all available technology combinations. This work hypothesizes that optimal decision-making on EFD technology selection can be achieved by an integrated approach, which allows decision-makers to minimize the environmental impact, to maximize the expected profits, to account for the influence of public perception, and, most importantly, to guarantee the operation's safety [9,10].

To support this hypothesis, two competing methods for the selection of EFD systems are presented in this

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paper. One follows a simple system selection approach where no formal consideration on the dependencies between the system components was considered (non-causal approach). The other takes into account the same drilling system components as in the previous approach but, in addition, introduces the effect of the dependencies between events taking place during the drilling operation (causal approach). As it is expected, the non-causal approach permits to reduce the computation time for the selection of the optimal drilling system, becoming a very good reference for preliminary analyses. On the other hand, the causal approach requires further knowledge on the dependencies taking place during the decision-making process, which adds computational effort to the optimal selection of EFD systems. Since the decision-making process is inherently conditioned in a drilling sequence (i.e., reservoir assessment dictates the drilling technologies to use, the area where the drilling is located dictates the technologies used to reduce emission, etc.), a comparison between both approaches seems convenient to address the relevance of interventions as the decision-making for the EFD system progresses. Irrespective of the method used, results show consistent support to the hypothesis that an integrated approach for the selection of EFD systems is needed to maximize the benefits of all stakeholders participating in an oil and gas related drilling operation.

To illustrate the benefits and limitations of the proposed methods (non-causal and causal), a case study is presented based on prescribed EFD system selection criteria for a drilling site located in Green Lake at McFaddin, TX, USA. The aim is to help decision-makers select an optimal drilling system for the site by minimizing environmental impact, maximizing profit, and at the same time accounting for perceptions and safety. In addition to showing the need for the use of an integrated decision-making approach on this case, the differences between each approach are discussed. Results of this comparative analysis show the relevance of introducing causal dependencies between system components during the search for the optimal selection of EFD systems.

Methods
Optimal drilling system selection
This section summarizes an optimal drilling system selection procedure for a given site [9]. The proposed system evaluation protocol defines a decision-making process that ensures the selection of an optimal drilling system according to given criteria.

The basis for an EFD system selection includes four main subsystems (Access, Drill Site, Rig, and Operation) and 13 subsets, which have been previously identified through standard EFD operations (see Figure 1). Design of the decision models has been undertaken as part of a comprehensive academic-industry collaboration funded by the US Department of Energy (DOE) and the Research Partnership to Secure Energy for America (RPSEA), which integrates the key drilling phases [2].

Once the subsystems and subsets are defined, available technologies within each subset need to be fully characterized. A drilling technology selection example is also presented in Figure 1, where technologies, indicated within circles for each subset box, represent one possible combination defining a drilling system. Further combinations of technologies are required to evaluate all possible systems and, consequently, to find the optimal drilling system for a given site [11].

For the proposed selection criteria, an attribute is defined as one of the parameters considered in the evaluation of the system (e.g., cost, footprint, emission, perceptions, and safety). Each attribute has an attribute scale used to score the technology on how well it meets the objective for this attribute (e.g., minimization of cost, footprint, and emissions and maximization of positive perceptions and safety value). To evaluate available technologies against each attribute, it is required to introduce attribute scales that explicitly reflect their possible impacts on the system selection process [12]. In this case, nine attributes and the corresponding scales are considered for the selection of the EFD system as shown in Figure 2. These attributes should describe accurately their corresponding technologies. Notice that the proposed attributes are measurable (i.e., dollars, hectares, and decibels) or constructed (i.e., perceptions and safety values) [9].

The attributes considered in this study are as follows:

- Total cost (x_1) = the total expenditure in dollars during the drilling operation.
- Footprint (x_2) = the total used land area in hectares.
- Emissions of air pollutants (x_3) = emissions of three air contaminants (i.e., carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM)). The relative importance of these contaminants is CO (20%), NO_x (40%), and PM (40%) as shown in Table 1. Table 1 shows an example of how to calculate the air emission score for each technology: First, estimate the three contaminants' real value for each technology in pounds per operating hour; second, in order to get an overall air emission score for each technology, transform each contaminant's score into a non-dimensional score (normalization) between 0 and 1 using the proportional scoring
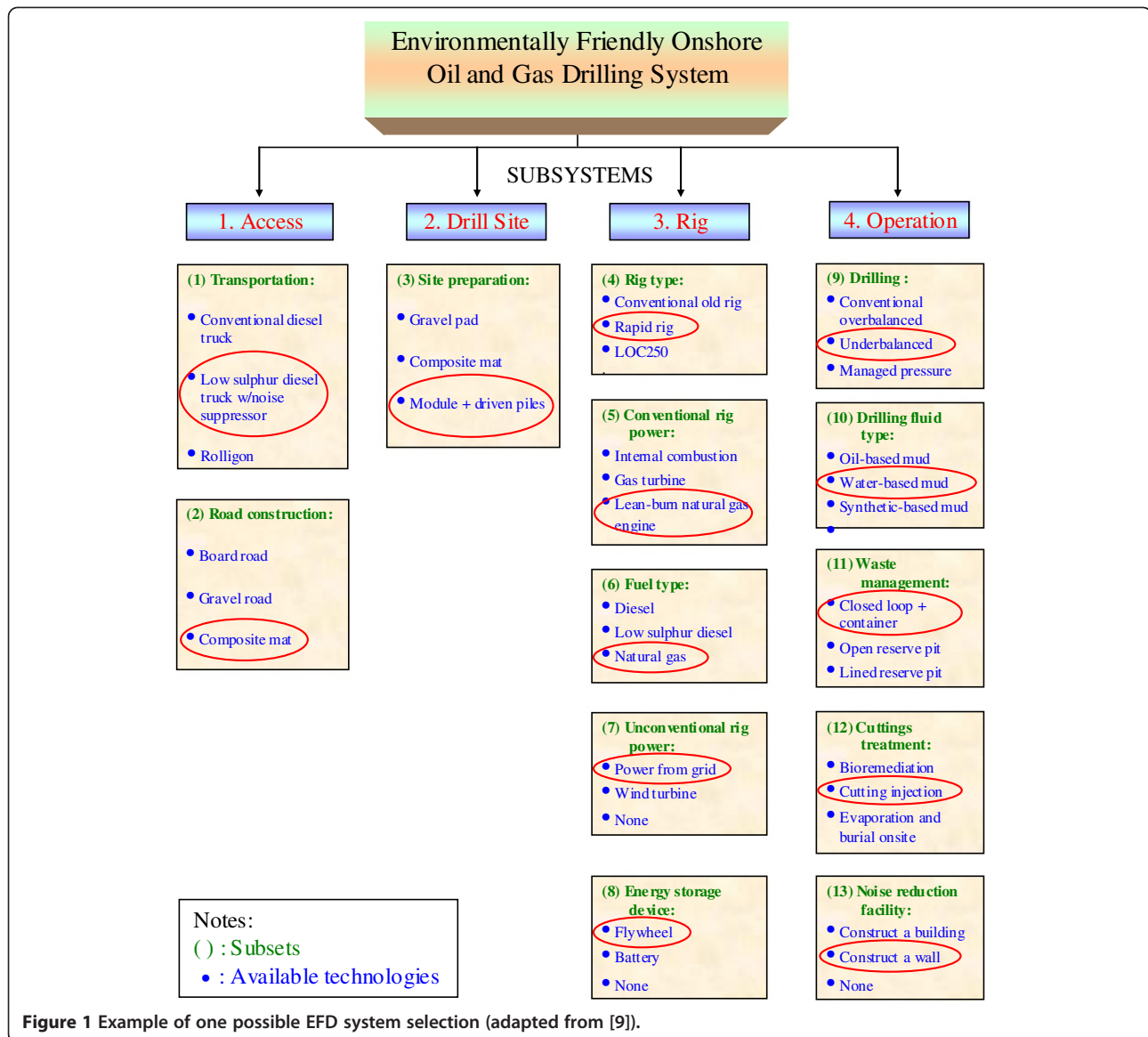
Figure 1 Example of one possible EFD system selection (adapted from [9]).

approach, (x – Worst score) / (Best score – Worst score); and third, calculate the overall air emission score of a technology as $\sum k_i u_i$ (where k_i is a weight factor for each air contaminant and u_i is a non-dimensional score for each contaminant).

- Emissions of solid and liquid pollutants (x_4) =? >thinsp;the ordinal scale as constructed in Table 2.
- Emissions of noise pollutants (x_5) = the 8-h time-weighted average (TWA) sound level given in decibels.
- Perception of government, as regulator, (x_6) = the ordinal scale as constructed in Table 3.
- Perception of industry, as decision maker, (x_7).
- Perception of the general public (x_8).

- Safety value (x_9).
- Notice that the ordinal scales of x_7 through x_9 are similar to that of x_6 [9].

To estimate the impact of available technologies with respect to the proposed nine attributes (i.e., x_1 through x_9), the decision method relies on experts' beliefs and on factual computations generated from available information sources. For instance, 'Composite mat (rent)', a selected technology for subset (2) 'Road construction', is estimated in terms of the required attributes based on the engineering calculations (cost, footprint, and emissions) and experts' beliefs (perceptions and safety) as shown in Table 4. It is noted that attribute scores are not evaluated for the empty cells because
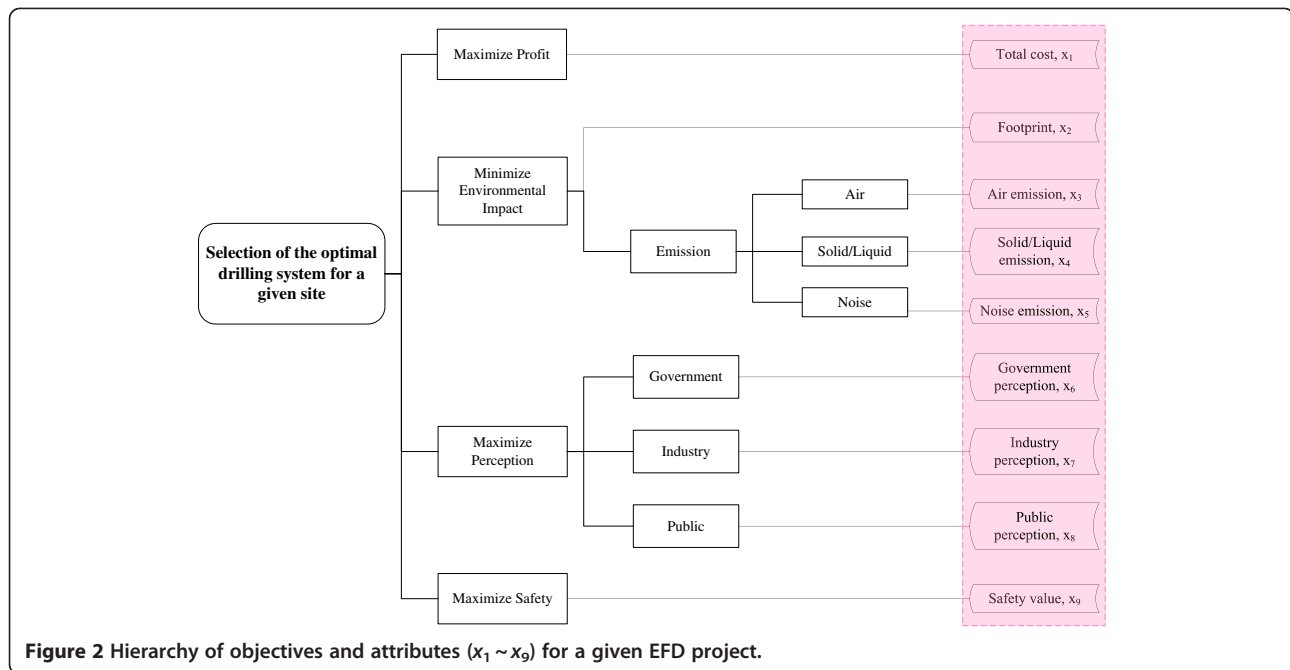
Figure 2 Hierarchy of objectives and attributes ($x_1 \sim x_9$) for a given EFD project.

those attribute scores are not relevant to the particular subsets or because these are already included in technologies within other subsets.

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 by selecting the minimum technology score of the system. The addition of individual scores is used for attributes such as cost, footprint, and emissions as indicated in Equation 1, while the minimum score is selected for attributes such as perceptions and safety as indicated in Equation 2. Accordingly, the overall score on the *i*th attribute (X_i) is as follows:

$$X_i = \sum_{n=1}^{N} x_{i,n} y_n \quad \text{for attributes } x_1 \text{ through } x_5 (\text{i.e.,} i = 1 \text{ to } 5),$$

(1)

$$X_i = \text{Min}\left[x_{i,n} y_n\right] \text{for attributes } x_6 \text{ through } x_9 (\text{i.e.,} i = 6 \text{ to } 9),$$

(2)

where n is the index for possible technologies, N is the number of possible technologies, i is the index for the attributes, $x_{i,n}$ is the score of the *n*th technology on the *i*th attribute, and y_n is a binary decision variable that is one if the *n*th technology is selected and zero if it is not.

The following constraint is required:

$$\sum_{n=1}^{M} y_n = 1 \text{ for each subset except subsets } (7), (8), \text{ and } (13),$$

(3)

where n is the index for possible technologies, M is the number of possible technologies within each subset, and y_n is a binary decision variable.

One technology must be selected for each subset, except for subsets (7), (8), and (13) since subsets (7), (8), and (13) are optional (see Figure 1). Table 4 shows the overall attribute score for each attribute of a system. It is observed from this table that 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), on the other hand, are calculated by choosing the worst score among technologies selected within each subset for a given system because it is suggested that perception and safety values should be included on the systems level, and 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 introduced to convert the overall dimensional score of a system into a non-dimensional utility value of the

Table 1 Example of air emission score calculation

Technologies	Unit	20% CO	40% NO$_x$	40% PM	Overall score
Gravel road: diesel truck + dust	g/hp-h	15.5	4	0.1	0.566
	lb/hp-h	0.03418	0.00882	0.00022	
	(lb/h)/unit	10.253	2.646	0.216	
	lb/operation	3,250.280	838.782	68.520	
	U-value	0.000	0.822	0.593	
Composite mat: low-sulphur diesel truck with noise suppressor	g/hp-h	15.5	0.2	0.01	0.976
	lb/hp-h	0.03418	0.00044	0.00002	
	(lb/h)/unit	10.253	0.132	0.007	
	lb/operation	369.117	4.763	0.238	
	U-value	0.886	0.999	0.999	
Internal combustion engine	lb/MWh	6.2	21.8	0.78	0.118
	(lb/h)/unit	6.200	21.800	0.780	
	(lb/h) × portion	6.200	21.800	0.780	
	lb/operation	1,339.200	4,708.800	168.480	
	U-value	0.588	0.000	0.000	
Internal combustion engine with SCR and with noise suppressor	(lb/MWh)	6.2	4.7	0.78	0.431
	(lb/h)/unit	6.200	4.700	0.780	
	(lb/h) × portion	6.200	4.700	0.780	
	lb/operation	1,339.200	1,015.200	168.480	
	U-value	0.588	0.784	0.000	
Lean-burn natural gas engines with noise suppressor	lb/MWh	5	2.2	0.03	0.878
	(lb/h)/unit	5.000	2.200	0.030	
	(lb/h) × portion	5.000	2.200	0.030	
	lb/operation	1,080.000	475.200	6.480	
	U-value	0.668	0.899	0.962	
Power from grid	lb/MWh	0	0	0	1.000
	(lb/h)/unit	0.000	0.000	0.000	
	(lb/h) × portion	0.000	0.000	0.000	
	lb/operation	0.000	0.000	0.000	
	U-value	1.000	1.000	1.000	

SCR, *selective catalytic reduction.*

Table 2 Proposed attribute scale for solid and liquid emissions

Waste management technologies	Cuttings treatment	Solid/liquid emission score
Closed loop	Cuttings injection	1.00
-	Bioremediation, composting, *in situ* vitrification, land spreading, plasma arc, microwave technology	0.75
Lined reserve pit	Thermal desorption	0.50
-	Chemical fixation and solidification	0.25
Open reserve pit	Evaporation and burial on-site	0.00

Table 3 Proposed attribute scale for government perception

Scale	Description	Perception score
Strong support	All parties will encourage its use and are willing to appropriate funds for the cause	1.00
Moderate support	There is interest from a majority. Its use will be encouraged, but funds will not be appropriated	0.75
Neutrality	All parties are indifferent. There is no resistance, but there is also no help	0.50
Moderate opposition	Some resistance from the majority. Its use may be discouraged, but fines or restrictions will not be imposed	0.25
Strong opposition	Strong resistance to its use from all parties. Restrictions or fines will be set up to eliminate this option	0.00

system, which ranges between 0 and 1. This allows the decision-makers to make the overall attribute score for each attribute uniform and comparable. Although Keeney and Raiffa [12] introduced the distinction between a value function and a utility function, the authors believe that this is still largely a personal choice within the decision analysis community. Herein, it is called a utility function since it is based on assessed preference parameters of a decision-maker and it represents their utility. Also, there are different approaches to develop single-attribute functions (i.e., linear and nonlinear). The proportional scoring approach (i.e., linear approach) is mainly used in this paper because of the limited expert

assessment. This can and should be revisited for future applications as needed based on interactions with EFD subject matter experts, mainly due to changes in technology. A general formula for the proportional scoring approach is given by [11]:

$$u_i(X_i) = \frac{X_i - \text{Worst score}}{\text{Best score} - \text{Worst score}}, \qquad (4)$$

where X_i is the overall score on the ith attribute of a system.

Figure 3 shows an example of utility function curves used in this study. As can be seen in Figure 3, the maximum and minimum values of each attribute need to be

Table 4 Example of a system matrix

Selected technologies in each subset	Weights ($\sum$=100% ∴ O.K!)								
	40%	25%	5%	5%	5%	5%	5%	5%	5%
	Total cost, x_1, ($)	Footprint, x_2, (ha)	Emissions ($x_3 \sim x_5$)			Perceptions ($x_6 \sim x_8$)			Safety value (x_9)
			Air	Solid and liquid	Noise (TWA)	Government	Industry	Public	
(1) Transportation: conventional diesel truck						0.250	1.000	0.250	0.750
(2) Road construction: composite mat (rent)	132,000	0.615	0.964		82.870	1.000	0.500	1.000	1.000
(3) Site preparation: composite mat (rent)	90,000	0.420	0.976		79.945	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	182,000		0.977		77.458	1.000	0.500	1.000	1.000
(5) Rig power (conventional): internal combustion engine with SCR and with noise suppressor	73,369		0.574		90.259	0.750	0.750	0.750	0.750
(6) Fuel type: low-sulphur diesel	47,628					0.750	0.750	1.000	0.750
(7) Rig power (unconventional): electric power from grid (10%)	5,918	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: flywheels	30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling technology: conventional overbalanced drilling	170,000				115.385	1.000	0.500	0.500	0.500
(10) Fluid type: water-based muds	47,940					1.000	1.000	1.000	1.000
(11) Waste management: closed loop + containers + solid control equipment[a]	30,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings management: cuttings injection	54,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction facility: N/A									
Overall attribute scores ($\sum$ or minimum value)	862,855	1.035	4.490	2.000	445.917	0.250	0.500	0.250	0.500
Single-attribute utility values (U_i)	0.883	0.764	0.757	1.000	0.655	0.250	0.500	0.250	0.500

∴ Multi-attribute utility value = 0.740; [a]solid control equipment includes shakers, possibly cone centrifuge, desander, desilter, cuttings dryer, and perhaps decanting centrifuge; CWD, casing-while-drilling; SCR, selective catalytic reduction; N/A, not applicable.

Figure 3 Examples of single-attribute utility function curves.
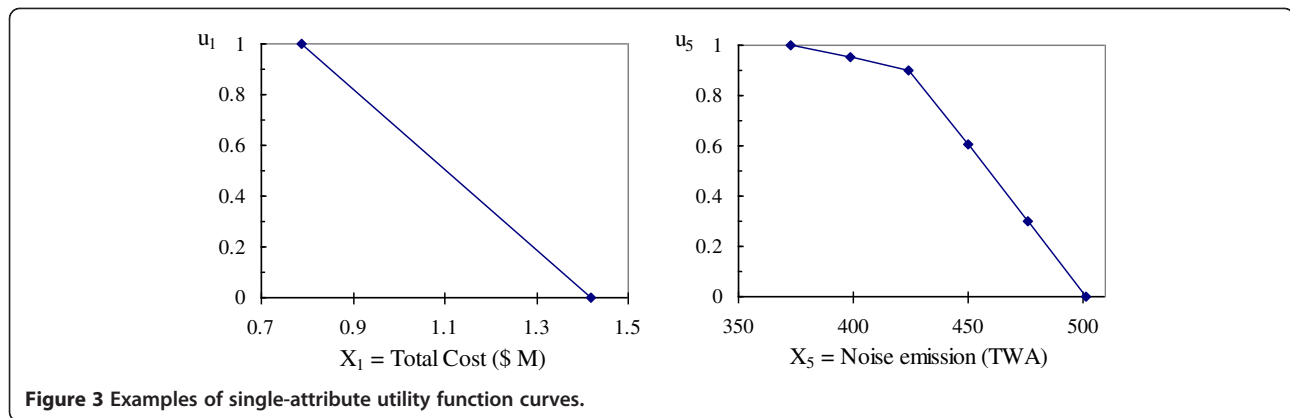
computed in order to generate the utility function curves. For example, it is known that the range of the cost attribute (X_1) values in Figure 3 is from $0.79 million to $1.42 million, where the minimum total costs are preferred over the maximum ones. Thus, to remain consistent with the scaling rule where the utility functions ranged from 0 to 1, u_1 ($0.79 million) = 1 and u_1 ($1.42 million) = 0 are defined. Simple linear curves are used for attributes x_1 through x_9 except x_5. The noise attribute (x_5) utility function discussed in Yu et al. [9] is modified in this paper in order to better satisfy the noise level in normal working conditions, as described by the Occupational Safety and Health Administration [13]:

$$u_5(X_5) = \frac{X_5 - \text{Worst score}}{425 - \text{Worst score}} \times 0.9 \text{ for } X_5 > 425, \tag{5}$$

$$u_5(X_5) = \frac{X_5 - 425}{\text{Best score} - 425} \times 0.1 + 0.9 \text{ for } X_5 \leq 425, \tag{6}$$

where X_5 is the noise attribute score, an 8-h TWA sound level in decibels, and u_5 is the noise attribute utility value of the system.

Once each single-attribute utility function $u_i(X_i)$ is derived for its attribute measure, these individual utility values are combined into a final utility value. If mutual preferential and utility independence are satisfied in this study, it is possible to define the multi-attribute utility function with the additive form [12]:

$$U(X_1, X_2, \ldots, X_9) = U\{u_1(X_1), u_2(X_2), \ldots, u_9(X_9)\}$$
$$= k_1 u_1(X_1) + \ldots + k_9 u_9(X_9) = \sum_{i=1}^{9} k_i u_i(X_i), \tag{7}$$

where $u_i(X_i)$ is the expected utility of the ith attribute scaled from 0 to 1, and k_i is the weighting constant for the ith attribute.

Since it is assumed that there is no interaction between each attribute (no cause-effect dependency), all of the weights are positive and they must sum to one [14]. The weight combination represents the trade-offs between the utility of the different attributes, and in practice, they are chosen by the stakeholders. One weight combination example assigned to a system is shown in Table 4. It is suggested to examine the appropriateness of any independence condition before adopting the additive utility function to see if violations of the independence condition are found [15]. In this study, for example, it was verified that the trade-offs for attributes x_1 (total cost) and x_2 (footprint), keeping the levels of the other attributes (x_3 through x_9) fixed, do not depend on the particular values of these fixed levels and so on for each pair of attributes.

Since the exhaustive search optimization is a simple, practical, and very robust method given the speed of modern computers [16], it is proposed to evaluate all possible systems according to nine attributes, with the relative importance of the different attributes (i.e., weight combination) defined by the stakeholders. Then, it follows to find the 'best' available system that should be particularly suitable for a specific site. Once all possible systems have been evaluated, the system containing the highest overall utility score is the best system with given weighting factors.

After the optimization scheme has determined 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 Table 4 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 result needs not be a single system but that a few 'optimal' systems close to the best score. This may provide some flexibility

Figure 4 Satellite map of Green Lake on the McFaddin Ranch, TX, USA (adapted from [9]).

Table 5 Available technologies for each subset

Subset number	Alternative #1	Alternative #2	Alternative #3
(1) Transportation	Conventional diesel truck	Low-sulphur diesel truck with noise suppressor	-
(2) Road construction	Gravel road	Composite mat (rent)	-
(3) Site preparation	Gravel pad	Composite mat (rent)	Aluminum modules + driven piles
(4) Rig type	Conventional rig	Rapid rig	LOC250 (CWD)
(5) Conventional power	Internal combustion engine	Internal combustion engine with SCR and with noise suppressor	Lean-burn natural gas engines with noise suppressor
(6) Fuel	Conventional diesel	Low-sulphur diesel	Natural gas
(7) Unconventional power	None	Electric power from grid (10% to 30%)	-
(8) Energy storage	None	Flywheel (10% to 30%)	-
(9) Drilling technology	Conventional overbalanced drilling	Underbalanced drilling with noise suppressor	Managed pressure drilling with noise suppressor
(10) Fluid	Water-based muds	-	-
(11) Waste management	Lined reserve pit + solid control equipment	Closed loop + containers + solid control equipment	-
(12) Cuttings treatment	Cuttings injection	CFS	-
(13) Noise reduction facility	None	-	-

SCR, *selective catalytic reduction;* CFS, *chemical fixation and solidification;* CWD, *casing-while-drilling.*

for the person in charge of the overall decision-making about the drilling process [15,17].

Results and discussion
Applications
To illustrate the applicability of an integrated approach for the selection of EFD systems, a case study was conducted at a site in Green Lake at McFaddin, TX, USA. This assumed that an independent operator was to drill a well on their lease in South Texas, located in an environmentally sensitive wetland area. The lease extends to the center of Green Lake on the McFaddin Ranch as shown in Figure 4. The formation target belongs to the upper Frio sand at a vertical depth of approximately 8,500 ft [18]. The available technologies within each subset for this case study are shown in Table 5. This table shows that some subsets (i.e., (3), (4), (5), and (9)) have three available technologies while subset (10) has only one available technology. It is also noticed that subset (13) is not considered in this case study.

Non-causal approach
An exhaustive search optimization generates all possible combinations of technologies for a given site. The corresponding influence diagram for this approach is shown in Figure 5. Notice that the configuration of the influence diagram for the non-causal system selection approach denotes no influences between the system's main components.

The influence diagram is a compact way for describing the dependencies among variables and decisions [19]. Normally, an arc in an influence diagram denotes an influence (i.e., the fact that the node at the tail of the arc influences the value of the node at the head of the arc).

These arcs are drawn as solid lines. Arcs coming into decision nodes have different meanings. As decision nodes are under the decision maker's control, these arcs do not denote influences but rather temporal precedence (in the sense of flow of information). The outcomes of all nodes at the tail of informational arcs will be known before the decision will need to be made. In particular, if there are multiple decision nodes, they need to be all connected by information arcs. This reflects the fact that the decisions are made in a sequence and the outcome of each decision is known before the next decision is made. Informational arcs are drawn as dashed lines [20]. Figure 5 shows a drilling system comprised of 13 subsets and the corresponding dependencies between them. In a real application, a non-causal system selection approach is not recommended as the best practice. However, this can help to assess preliminary responses of the system selection due to its simple implementation and efficient computational effort. Moreover, it typically serves as the basis for the development of more complex system selections.

Only three basic dependencies were considered in this specific application as shown in Figure 6 (i.e., dependencies between subsets (5) and (7), between subsets (5) and (6), and between subsets (7) and (8)). For example, the number of possible fuel types for a conventional power generation engine varies by what kind of engine is selected and whether using an energy storage device or not should be dependent on whether an unconventional power generation method is used or not. If it is decided not to use an unconventional power generation method, an energy storage device is not considered as a possible subset in the 'Rig' subsystem. In this case study, the range of unconventional power usage is varied from 0% to 30% of total power usage (see Figure 6). The
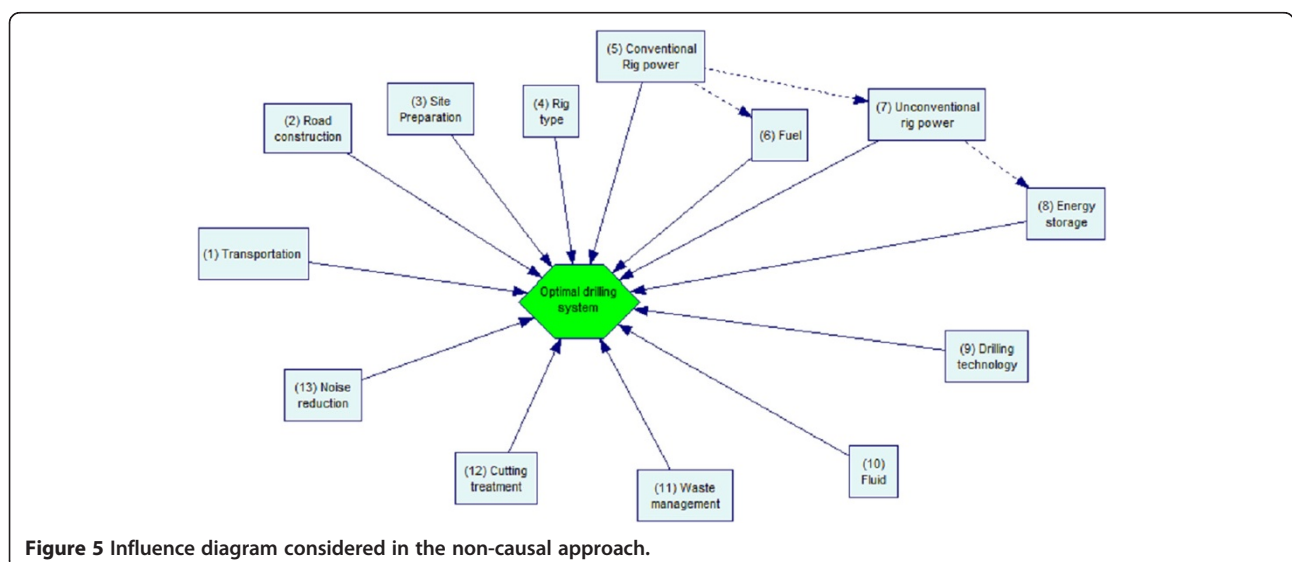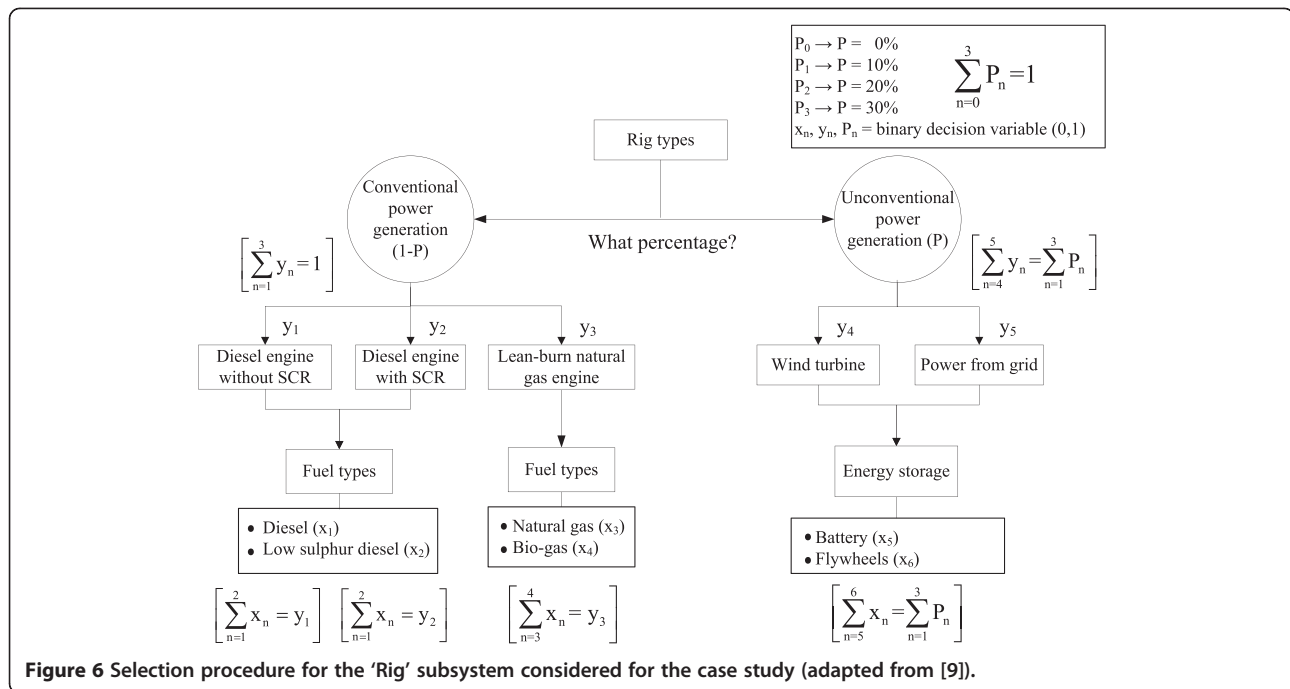

Figure 5 Influence diagram considered in the non-causal approach.

Figure 6 Selection procedure for the 'Rig' subsystem considered for the case study (adapted from [9]).

construction strategy and constraints for the 'Rig' subsystem are also specified in Figure 6 [9].

The basic assumptions and an example of input spreadsheet used to evaluate available technologies for this case study are shown in Tables 6 and 7, respectively. Since this application does not consider varying drilling time, the total drilling time was fixed to 16 days for the computation of total cost. Other attribute values such as emissions were also evaluated considering the same drilling time.

Causal approach

To take into account causal dependencies for the selection of an optimal drilling system, it is necessary to build a consistent influence diagram. In this case, the influence diagram for the given drilling site was developed through a series of meetings with EFD experts, and it is presented in Figure 7 [9]. Notice that the effort required to build the causal model is significantly higher than the

Table 6 Basic assumptions used in the formulation of the non-causal approach

Basic assumptions	Value
Power consumption (peak)	1 MW
Access road width	7.6 m (2 lanes)
Access road length	1.6 km
Width of drilling site	107 m
Length of drilling site	107 m
Total drilling time	16 days

effort required to build the model for the non-causal approach because it requires deeper knowledge between the dependencies of the system components. The influence diagram representing dependencies between the subsets should be considered before estimating attribute scores of technologies because attribute scores of a technology can be dependent on key influence variables as those presented in Table 8. This table includes the basic assumptions considered for the case study as well as key input variables that affect the proposed technologies.

To illustrate the impact of considering dependencies between the EFD subsets, it is suggested to first consider the influence of a selected rig type in subset (4) causing the estimate of total drilling time (i.e., 10 to 16 days) because the total drilling time causes the various estimates of attribute scores of technologies within many different subsets (i.e., total cost, emissions, etc.). For example, it is necessary to estimate different total costs for the same technology within subset (5) 'Conventional rig power' based on 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; total drilling time causes the variation of total cost of a technology. The total cost of the same technology within subset (2) 'Road construction' also varies by a selected transportation type in subset (1) because it is likely that the mobilization cost of a technology within subset (2) increases as a more expensive transportation type is selected. Moreover, the total footprint of the same technology within subset (3) 'Site
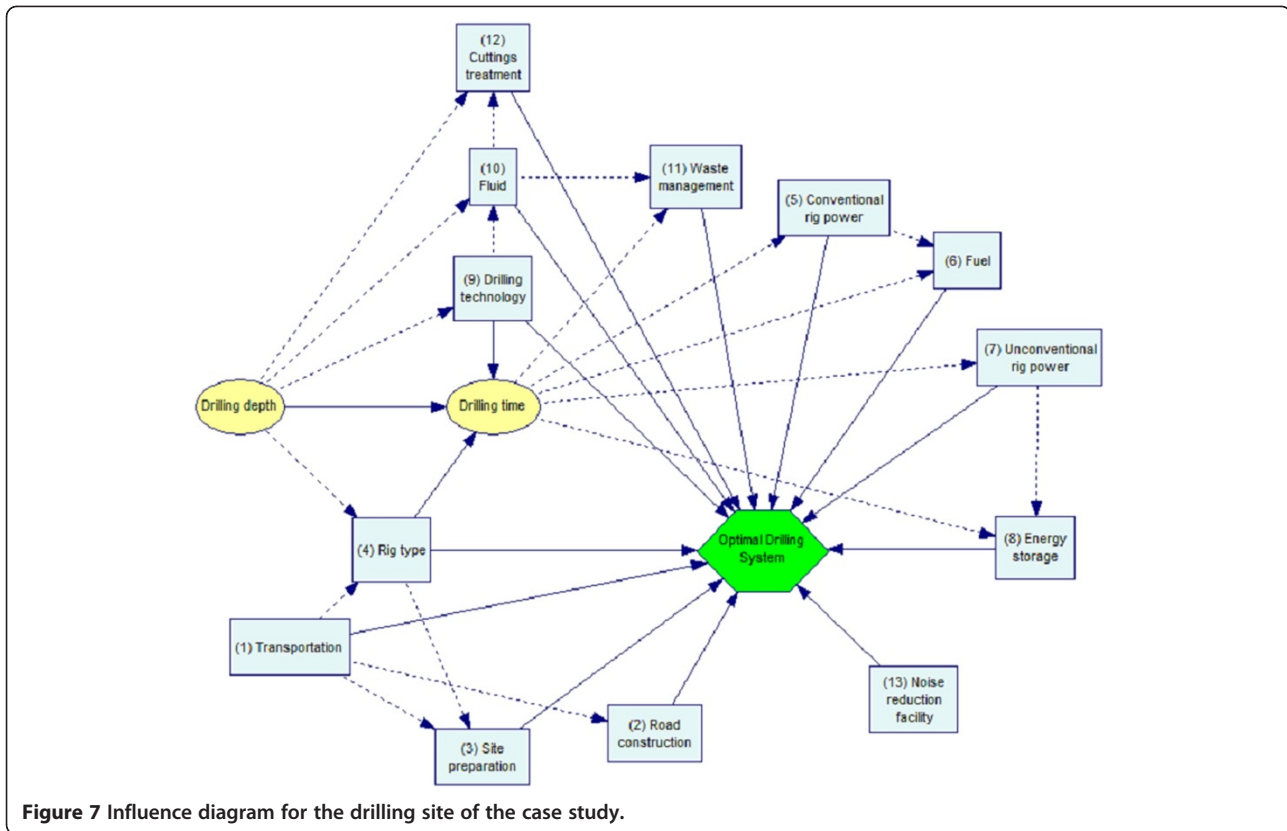
Table 7 Example of input scores used in the non-causal approach

Subsets	Technologies	Buy ($)	Resell value ($)	Rent/ day ($)	Daily rate ($)	Total cost ($)	Ecological footprint (ha)	Emissions			Perceptions			Safety value
								Air	Solid and liquid	Noise (TWA)	Government	Industry	Public	
1	Conventional diesel truck					20,000	0.000				0.250	1.000	0.250	0.750
	Low-sulphur diesel truck with tier III engine and with noise suppressor					28,000	0.000				1.000	0.500	1.000	0.750
2	Gravel roads					148,500	1.226	0.570		99.000	0.250	1.000	0.250	0.500
	Composite mat					132,000	0.613	0.960		83.000	1.000	0.500	1.000	1.000
3	Gravel pad					137,000	1.133	0.600		98.000	0.250	1.000	0.250	0.500
	Composite mat					120,000	0.567	0.970		82.000	0.750	0.750	0.750	1.000
	Aluminum modules + driven piles					220,000	0.003	0.970		97.600	1.000	0.500	1.000	0.500
4	Conventional order vintage rig					200,000		0.970		79.000	0.500	1.000	0.500	0.500
	Rapid rig					224,000		0.970		77.000	1.000	0.500	1.000	1.000
	LOC250 (CWD)					240,000		0.980		77.500	1.000	0.500	1.000	1.000
5	Internal combustion engine					56,000		0.384		107.000	0.500	1.000	0.500	0.750
	Internal combustion engine with SCR and with noise suppressor					83,020		0.601		90.000	0.750	0.750	0.750	0.750
6	Conventional diesel					65,800					0.500	1.000	0.500	0.500
	Low-sulphur diesel					69,160					0.750	0.750	1.000	0.750
7	Electronic power from grid					25,800.00	0.000	1.000		0.000	0.500	1.000	1.000	1.000
8	Flywheels	450,000	360,000			90,000	0.000				0.500	1.000	1.000	0.750
9	Conventional overbalanced drilling					204,000				117.000	1.000	0.500	0.500	0.500
	Underbalanced drilling with noise suppressor					221,400				101.000	0.750	0.750	0.750	0.750
	Managed pressure drilling with noise suppressor					232,200				99.000	0.750	0.750	1.000	1.000
10	Water-based muds					48,000					1.000	1.000	1.000	1.000
11	Lined reserve pit + solid control equipment[a]					24,000	0.015		0.500		0.750	0.750	0.750	0.750
	Closed loop + containers + solid control equipment[a]					36,000	0.000		1.000		1.000	0.500	1.000	0.750
12	Cuttings injection					54,000			1.000		1.000	0.500	1.000	0.750
	CFS					61,710			0.250		0.750	0.750	1.000	0.500
13	N/A													

[a]Solid control equipment includes shakers, possibly cone centrifuge, desander, desilter, cuttings dryer, and perhaps decanting centrifuge; CWD, casing-while-drilling; SCR, selective catalytic reduction; CFS, chemical fixation and solidification; N/A, not applicable.

Figure 7 Influence diagram for the drilling site of the case study.

preparation' varies by a selected rig type in subset (4) because each rig type uses different land area. All the other causal dependencies can be easily established by following Figure 7.

An example of an input spreadsheet used to assign scores to different technologies is presented in Table 9. Notice that the cost, footprint, and emission scores of a technology in subset (1) 'Transportation' are already included in a mobilization part of technologies within other subsets. For example, the total cost of gravel road in subset (2) shown in Table 9 includes material, mobilization, and installation costs.

Analysis of results

A base-case weight combination is defined as shown in Table 10 to compare the optimal drilling systems selected by the non-causal and causal approaches. The resulting optimal drilling systems are presented in Tables 11 and 12.

Basic comparisons between these tables indicate, for instance, that in subset (4) 'Rig type', a conventional rig is always selected in terms of the cost attribute in the non-causal approach because the daily cost of LOC250 rig ($15,000) is more expensive than a conventional rig ($12,500). On the other hand, LOC250 rig is always selected in the causal approach because it takes into account total drilling time variation and LOC250 rig

reduces the total drilling time by 5 days compared to a conventional rig. Therefore, the total costs of LOC250 rig and a conventional rig in the non-causal approach are $240,000 (16 days × $15,000) and $200,000 (16 days × $12,500), respectively, whereas $165,000 (11 days × $15,000) and $200,000 (16 days × $12,500), respectively, in the causal approach. This result shows that the causal approach yields a more systematic system selection - considering total drilling time variation. In addition, both findings support the main hypothesis of this work, stressing that unnecessary costs would be generated in the absence of an integrated decision-making model.

Other relevant inferences can be obtained by following an integrated decision-making approach for the selection of EFD systems. This can be illustrated by comparing the benefits and limitations between the proposed models when varying the weight on the cost attribute from zero to one, as shown in Tables 13 and 14. It is noted that since the weights must sum to one, as one weight increases, the 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 10. Underbalanced drilling (UBD) and managed pressure drilling (MPD) methods are mainly selected as an optimal drilling system's component in the causal approach because USB or MPD methods can reduce a system's

Table 8 Basic assumptions and key influence variables used in formulation of the causal approach

Basic assumptions and key influence variables	Value
Basic assumptions	
Power consumption (peak)	1 MW
Access road width	7.6 m (2 lanes)
Access road length	1.6 km
Width of drilling site	107 m (conventional rig + pad)
	91 m (conventional rig + modules + piles)
	61 m (compact rig + pad)
	46 m (compact rig + modules + piles)
Length of drilling site	107 m (conventional rig + pad)
	91 m (compact rig + pad)
	38 m (conventional rig + modules + piles)
	30 m (compact rig + modules + piles)
Key influence variables	
Transportation type	Conventional diesel truck
Rig type	LOC250 (CWD)
Engine type	Internal combustion engine
Drilling type	Conventional overbalanced drilling
Noise reduction type	N/A
Proportion of unconventional power	30.0%
Resale value	80.0%
Drilling time	9.0 days
Move/rig up	1.0 day
Number of wells	1 well

CWD, *casing-while-drilling*; N/A, *not applicable*.

total cost due to the decreased drilling time, compared to conventional overbalanced drilling (COBD) method. In the non-causal approach, however, once the weight factor of the cost attribute is greater than 33%, COBD is selected as an optimal drilling system's component because its daily cost is cheaper than that of UBD or MPD.

The technologies in subsets (2), (4), (10), (12), and (13) selected by the causal approach shown in Table 14 are always the same for all possible weights on the cost attribute, while selected technologies in other subsets can change. For example, 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'. It is anticipated that further sensitivity analyses need to be conducted for other input variables, including attribute scores and the utility functions for each attribute, in addition to weighting factors for attributes to suggest more robust optimal systems for this case study.

In summary, LOC250 rig, UBD, and MPD, which can reduce the total drilling time causing the reduction of cost, footprint, and emissions, are most likely to be selected as components of optimal drilling systems when following the causal approach. It is reasonable to state that if one technology can cause to reduce other technologies' cost, footprint, and emissions, it can be selected as a component of an optimal drilling system even if its daily cost is more expensive than that of other alternatives. The causal approach thoroughly takes into account this kind of dependencies between each drilling component, as opposed to just reflecting the exhaustive search of optimal technologies (i.e., less expensive conventional technologies) in the non-causal approach. Therefore, results of this case study suggest that the causal approach generates improved inferences that can better guide the decision-making process for the optimal

Table 9 Example of input scores of the case study in the formulation of the causal approach

Subsets	Technologies	Buy ($)	Resell value ($)	Rent/ day ($)	Daily rate ($)	Total cost ($)	Ecological footprint (ha)	Emissions			Perceptions			Safety value
								Air	Solid and liquid	Noise (TWA)	Government	Industry	Public	
1	Low-sulphur diesel truck with tier III engine and with noise suppressor										1.000	0.500	1.000	0.750
2	Gravel roads	198,396	0		12,400	198,396	1.226	0.679		77.250	0.250	1.000	0.250	0.500
	DURA-BASE from composite mat (rent)					147,840	0.613	0.976		64.696	1.000	0.500	1.000	1.000
3	Gravel pad	184,118	0		11,507	184,118	1.138	0.702		76.815	0.250	1.000	0.250	0.500
	DURA-BASE from composite mat (rent)					137,200	0.569	0.978		64.194	0.750	0.750	0.750	1.000
	Aluminum modules + driven piles	1,870,041	1,496,033		23,376	374,008	0.003	0.983		77.990	1.000	0.5000	1.0000	0.500
4	Traditional older vintage rig			12,500	12,500	228,000		0.982		61.304	0.500	1.000	0.500	0.500
5	Internal combustion engine			3,500	3,500	56,000		0.382		106.775	0.500	1.000	0.500	0.750
	Internal combustion engine with SCR and with noise suppressor			5,188	5,188	83,003		0.602		89.574	0.750	0.750	0.750	0.750
6	Conventional diesel			4,704	4,704	65,856					0.500	1.000	0.500	0.500
	Low-sulphur diesel			4,939	4,939	69,149					0.750	0.750	1.000	0.750
7	Electrical power from grid			1,614	1,614	25,824.00	0.000	1.000		0.000	0.500	1.000	1.000	1.000
8	Flywheels	450,000	360,000		5,625	90,000	0.000				0.500	1.000	1.000	0.750
9	Conventional over balanced drilling			17,000	17,000	204,000				116.700	1.000	0.500	0.500	0.500
10	Water-based muds					47,940					1.000	1.000	1.000	1.000
11	Lined reserve pit + solid control equipment[a]			2,000	2,000	24,000	0.015		0.500		0.750	0.750	0.750	0.500
	Closed loop + containers + solid control equipment[a]			3,000	3,000	36,000	0.000		1.000		1.000	0.500	1.000	0.750
12	Cuttings injection			5,000	5,000	54,000			1.000		1.000	0.500	1.000	0.750
	CFS					61,710			0.250		0.750	0.750	1.000	0.500
13	N/A													

[a]Solid control equipment includes shakers, possibly cone centrifuge, desander, desilter, cuttings dryer, and perhaps decanting centrifuge; SCR, selective catalytic reduction; CFS, chemical fixation and solidification; N/A, not applicable.

Table 10 Base-case weight combination

Attributes	Weights ($\sum = 1$)
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

selection of EFD systems for a given site. However, it is worth mentioning that the main limitation of the causal approach is associated to the effort needed to build the decision-making model (i.e., availability of knowledge base, time, and cost).

A limitation that applies to the use of an integrated decision-making approach for the selection of EFD systems relies on the use of multi-attribute utility values, which typically represent deterministic estimates. This may contain significant uncertainty components, such as total drilling time and drilling depth, which affect the

rest of the decision-making process. This limitation represents a challenge in terms of future research, which should aim at providing a confidence metric on the predictions of the integrated approach models proposed above.

Nevertheless, what is consistently observed from the use of the integrated decision-making models discussed above is a significant increase in the number of inferences that becomes available to the stakeholders, contributing to a more informed decision-making process. In addition, the proposed models set the basis to 'connect' with the peripheral decision-making processes, such as those mentioned before, related to impacts to current and future civil infrastructure and their inherent environmental impacts. In particular, because of the imminent growth of the natural gas industry across the country, it becomes a matter of urgency to improve the understanding of the decision-making of these processes as well as of the collateral consequences stemmed from related disciplines.

Web-based decision optimization tools

Finally, to further illustrate the applicability of the proposed models, and its readability to connect to other concurrent disciplines, these have been put into the

Table 11 Example of an optimal drilling system selected by the non-causal approach

Selected technologies in each subset	Weights ($\sum = 100\%$ ∴ O.K!)								
	40%	20%	6.67%	6.67%	6.67%	5%	5%	5%	5%
	Total cost, x_1, ($)	Footprint, x_2, (ha)	Emissions ($x_3 \sim x_5$)			Perceptions ($x_6 \sim x_8$)			Safety value (x_9)
			Air	Solid and liquid	Noise (TWA)	Government	Industry	Public	
(1) Transportation: conventional diesel truck	20,000					0.250	1.000	0.250	0.750
(2) Road construction: composite mat (rent)	132,000	0.627	0.960		83.000	1.000	0.500	1.000	1.000
(3) Site preparation: composite mat (rent)	120,000	0.567	0.970		82.000	0.750	0.750	0.750	1.000
(4) Rig type: conventional older vintage rig	200,000		0.970		79.000	0.500	1.000	0.500	0.500
(5) Rig power (conventional): lean-burn natural gas engines with noise	125,000		0.880		93.000	0.250	1.000	0.250	1.000
(6) Fuel type: natural gas	58,800					1.000	0.500	1.000	0.750
(7) Rig power (unconventional): N/A (0%)	0	0.000	1.000		0.000	0.250	1.000	0.250	1.000
(8) Energy storage: N/A	0	0.000				0.250	1.000	0.250	1.000
(9) Drilling technology: conventional over balanced drilling	204,000				117.000	1.000	0.500	0.500	0.500
(10) Fluid type: water-based muds	48,000					1.000	1.000	1.000	1.000
(11) Waste management: closed loop + containers+ solid control equipment[a]	36,000	0.000		1.000		1.000	0.500	1.000	0.750
(12) Cuttings management: cuttings injection	54,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction facility: N/A									
Overall attribute scores ($\sum$ or minimum value)	997,800	1.194	4.780	2.000	454.000	0.250	0.500	0.250	0.500
Single-attribute utility values(U_i)	0.929	0.679	0.971	1.000	0.565	0.250	0.500	0.250	0.500

∴ Multi-attribute utility value = 0.751; [a]solid control equipment includes shakers, possibly cone centrifuge, desander, desilter, cuttings dryer, and perhaps decanting centrifuge; N/A, not applicable.

Table 12 Example of an optimal drilling system selected by the causal approach

Selected technologies in each subset	Weights ($\sum$ = 100% $\therefore$ O.K!)								
	40%	20%	6.67%	6.67%	6.67%	5%	5%	5%	5%
	Total cost, x_1, ($)	Footprint, x_2, (ha)	Emissions ($x_3 \sim x_5$)			Perception ($x_6 \sim x_8$)			Safety value (x_9)
			Air	Solid and liquid	Noise (TWA)	Government	Industry	Public	
(1) Transportation: low-sulphur diesel truck with noise suppressor						1.000	0.500	1.000	0.750
(2) Road construction: composite mat (rent)	147,840	0.613	0.976		64.696	1.000	0.500	1.000	1.000
(3) Site preparation: composite mat (rent)	100,800	0.418	0.984		62.356	0.750	0.750	0.750	1.000
(4) Rig type: LOC250 (CWD)	173,800		0.985		60.366	1.000	0.500	1.000	1.000
(5) Rig power (conventional): lean-burn natural gas engines with noise suppressor	70,353		0.918		89.499	1.000	0.500	1.000	0.750
(6) Fuel type: natural gas	25,650					1.000	0.500	1.000	0.750
(7) Rig power (unconventional): electric power from grid (10%)	5,380	0.000	1.000		0.000	0.500	1.000	1.000	1.000
(8) Energy storage: flywheels	30,000	0.000				0.500	1.000	1.000	0.750
(9) Drilling technology: underbalanced drilling with noise suppressor	184,500				99.624	0.750	0.750	0.750	0.750
(10) Fluid type: water-based muds	47,940					1.000	1.000	1.000	1.000
(11) Waste management: closed loop + containers + solid control equipment[a]	27,000			1.000		1.000	0.500	1.000	0.750
(12) Cuttings management: cuttings injection	54,000			1.000		1.000	0.500	1.000	0.750
(13) Noise reduction facility: N/A								1.000	
Overall attribute scores ($\sum$ or minimum value)	867,263	1.031	4.863	2.000	376.542	0.500	0.500		0.750
Single-attribute utility values (U_i)	0.876	0.764	0.986	1.000	0.993	0.500	0.500		0.750

$\therefore$ Multi-attribute utility value = 0.827; [a]*solid control equipment includes shakers, possibly cone centrifuge, desander, desilter, cuttings dryer, and perhaps decanting centrifuge*; N/A, not applicable.

Table 13 Optimal systems selected by the non-causal approach

Subset number	Set 1 (0% $\leq w_1$ < 20%)	Set 2 (20% $\leq w_1$ < 33%)	Set 3 (33% $\leq w_1$ < 64%)	Set 4 (64% $\leq w_1 \leq$ 100%)
(1)	Low-sulphur diesel truck with noise suppressor	Low-sulphur diesel truck with noise suppressor	Conventional diesel truck	Conventional diesel truck
(2)	Composite mat (rent)	Composite mat (rent)	Composite mat (rent)	Composite mat (rent)
(3)	Aluminum modules + driven piles	Composite mat (rent)	Composite mat (rent)	Composite mat (rent)
(4)	Rapid rig	Rapid rig	Conventional rig	Conventional rig
(5)	Lean-burn natural gas engines with noise suppressor	Lean-burn natural gas engines with noise suppressor	Lean-burn natural gas engines with noise suppressor	Internal combustion engine
(6)	Natural gas	Natural gas	Natural gas	Conventional diesel
(7)	Electric power from grid (10%)	Electric power from grid (10%)	None	None
(8)	Flywheel	Flywheel	None	None
(9)	Managed pressure drilling with noise suppressor	Underbalanced drilling with noise suppressor	Conventional overbalanced drilling	Conventional overbalanced drilling
(10)	Water-based muds	Water-based muds	Water-based muds	Water-based muds
(11)	Closed loop + containers + solid control equipment[a]	Closed loop + containers + solid control equipment[a]	Closed loop + containers + solid control equipment[a]	Lined reserve pit + solid control equipment[a]
(12)	Cuttings injection	Cuttings injection	Cuttings injection	Cuttings injection
(13)	None	None	None	None

The weight on the cost attribute (w_1) is varied from 0 to 1; [a]*solid control equipment includes shakers, possibly cone centrifuge, desander, desilter, cuttings dryer, and perhaps decanting centrifuge.*

Table 14 Optimal systems selected by the causal approach

Subset number	Set 1 (0% $\leq w_1 < 2\%$)	Set 2 (2% $\leq w_1 < 27\%$)	Set 3 (27% $\leq w_1 < 48\%$)	Set 4 (48% $\leq w_1 < 81\%$)	Set 5 (81% $\leq w_1 \leq 100\%$)
(1)	Low-sulphur diesel truck with noise suppressor	Low-sulphur diesel truck with noise suppressor	Low-sulphur diesel truck with noise suppressor	Conventional diesel truck	Conventional diesel truck
(2)	Composite mat (rent)	Composite mat (rent)	Composite mat (rent)	Composite mat (rent)	Composite mat (rent)
(3)	Aluminum modules + driven piles	Aluminum modules + driven piles	Composite mat (rent)	Composite mat (rent)	Composite mat (rent)
(4)	LOC250 (CWD)	LOC250 (CWD)	LOC250 (CWD)	LOC250 (CWD)	LOC250 (CWD)
(5)	Lean-burn natural gas engines with noise suppressor	Lean-burn natural gas engines with noise suppressor	Lean-burn natural gas engines with noise suppressor	Lean-burn natural gas engines with noise suppressor	Internal combustion engine
(6)	Natural gas	Natural gas	Natural gas	Natural gas	Conventional diesel
(7)	Electric power from grid (30%)	Electric power from grid (10%)	Electric power from grid (10%)	None	None
(8)	Flywheel	Flywheel	Flywheel	None	None
(9)	Managed pressure drilling with noise suppressor	Managed pressure drilling with noise suppressor	Underbalanced drilling with noise suppressor	Underbalanced drilling with noise suppressor	Underbalanced drilling with noise suppressor
(10)	Water-based muds	Water-based muds	Water-based muds	Water-based muds	Water-based muds
(11)	Closed loop + containers + solid control equipment[a]	Closed loop + containers + solid control equipment[a]	Closed loop + containers + solid control equipment[a]	Closed loop + containers + solid control equipment[a]	Lined reserve pit + solid control equipment[a]
(12)	Cuttings injection	Cuttings injection	Cuttings injection	Cuttings injection	Cuttings injection
(13)	None	None	None	None	None

The weight on the cost attribute (w_1) is varied from 0 to 1; [a]*solid control equipment includes shakers, possibly cone centrifuge, desander, desilter, cuttings dryer, and perhaps decanting centrifuge; CWD, casing-while-drilling.*

form of two web-based decision optimization tools (non-causal and causal), replicating the system selection processes discussed above. These applications provide a quantitative basis for suggesting appropriate EFD systems, which explicitly evaluate the proposed selection criteria and allow for using the best available evidence, including expert's belief, data, and models.

The non-causal approach has been already used by students enrolled in the 'Drilling Engineering (PETE661)' class at Texas A&M University as an integrated decision-making tool for their well site design [21]. More recently, the causal application was completed and used for the same course, allowing for the generation of similar inferences and comparisons as discussed in this work. The key features of both applications are summarized in Table 15 and can be accessed at [22].

Conclusions

This work makes the case for introducing an integrated decision-making approach for the selection of optimal environmentally friendly drilling (EFD) systems to provide a more logical and comprehensive approach that maximized the economic and environmental goals of both the landowner and the natural gas industry. Two different drilling system selection approaches were discussed based on a combination of the multi-attribute utility theory and the exhaustive search optimization, which are formulated as a non-causal and a causal approach. The proposed models were implemented to a case study defined in an environmentally sensitive area in Green Lake at McFaddin, TX, USA.

Results showed the relevance of using an integrated decision-making approach for the selection of EFD

Table 15 Key features of the two web-based decision-making optimization tools

Features	Non-causal	Causal
Providing a quantitative basis for selecting EFD drilling systems	Included	Included
Evaluating different EFD drilling technologies	Included	Included
Optimizing selection of EFD systems for given conditions	Included	Included
Introducing drilling time variation effects	Not included	Included
Introducing causal dependencies between the system components	Not included	Included

systems. This was corroborated by assessing each model and by showing the type of inferences that can be retrieved from the definition of such a complex system. A comparison between the proposed models also helped to address the need for the use of an integrated decision-making approach because it was possible to replicate the real trade-off between technology costs and reduction of the environmental impacts.

The proposed decision-making methods aim at indicating a critical shift from non-causal to causal system selection, which the authors strongly believe can improve the finding of optimal components in such a complex system as of EFDs. By having access to such decision-making models, optimal scenarios can be suggested, contributing to a more informed decision-making process. This becomes significantly relevant in light of an imminent growth of the natural gas industry and the potential consequences this may impose in concurrent processes such as those related to civil infrastructure and its corresponding environmental impacts.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

OY carried out the optimization studies and drafted the manuscript. ZMC drafted the manuscript. SG participated in the optimization study and analyzed the results. JB and DB conceived of the study and participated in its design and coordination. All authors read and approved the final manuscript.

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