A feature-based well completion optimization system applying fuzzy MCDM

by

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Abstract

Well completion is an intermediate process for oil production, or simply a connection between well drilling and oil recovery, it can influence wells' productivity, stability and longevity directly, hence has important effect on economic benefit of oilfield development. The selection of well completion method involves a wide range of knowledge, and multiple perspectives to be considered. However, almost all the commonly adopted well completion selection models and methods are not comprehensive. Some of them depend only on experts' knowledge, experience and judgement, which are too subjective and cannot cover all the aspects needed to be considered during the selection. Others only depend on numerical indexes, like initial production, operation cost etc., which ignore experts' knowledge and are overly simplified. Therefore, this thesis is intended to build an optimum well completion method selection system to provide a solution for this multi-objective problem.

Research works included in this thesis are briefly described as follows.

- Establishing rules for well completion method selection. This thesis summarizes these commonly used well completion methods for both vertical and horizontal wells, and their applicable conditions, advantages and disadvantages are analyzed to help proposing selection rules of well completion methods.
- Building an evaluation prototype system. Five primary evaluation aspects are included: reservoir failure mode identification, stimulation technology determination, productivity, cost and HSE. Each of these criteria has its own corresponding second level indexes, and both qualitative and quantitative indexes are included in this system.

- Proposing a new object data structure to support the software development feature. Well completion method selection feature is proposed, this feature not only can integrate different expert areas together to support the complex decision-making process, but also can reduce rework and iterations. In addition, using the feature modelling approach can bring all independent modules together to describe the full system in a coordinated and comprehensive way. Therefore, with this newly defined feature as a generic solution mechanism, this system can be expanded easily to include new well completion methods and evaluation indexes.
- Building a new weight determination scheme for well completion selection. The new scheme not only combines subjective and objective method together, but also integrates MODM and MADM into one system.
- Applying the proposed selection system on two different cases to demonstrate the feasibility of this system and developing a well completion methods optimum selection software prototype with C# language.

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During the study, I have learned more knowledge from my supervisor and other fellow students in our group, I have enjoyed the time spending with them.

Special thanks are owed to my parents, who have supported me throughout my years of education, both morally and financially.

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List of Abbreviations

AHP	Analytic Hierarchy Process
MCDM	Multiple Criteria Decision Making
MODM	Multiple Objective Decision Making
MADM	Multiple Attribute Decision Making
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
ELECTRE	Elimination and Choice Expressing the Reality
MOPA	Multi Objective Programming Approach
PROMETHEE	Preference Ranking Organization Method for Enrichment
GRA	Grey Relational Analysis
API	American Petroleum Institute
NPV	Net Present Value
HSE	Health, safety and environment
EPI	Environment Protection Index
SODM	Single-Objective Decision-Making
ECP	External Casing Packer

Chapter 1: Introduction

1.1 Background

Completions are the interface between the reservoir and surface production [1]. A good well completion method can build effective connections between reservoir and wellhole based on reservoir's geological characteristics and technical requirements of exploitation.

Well completion is a technology involves a wide range of knowledge and is also a crucial part in petroleum engineering, which connects well drilling with oil recovery. As shown in Figure 1.1 (Jonathan, 2009), completion engineer interacts with people from different disciplines and grasps knowledge from different fields.

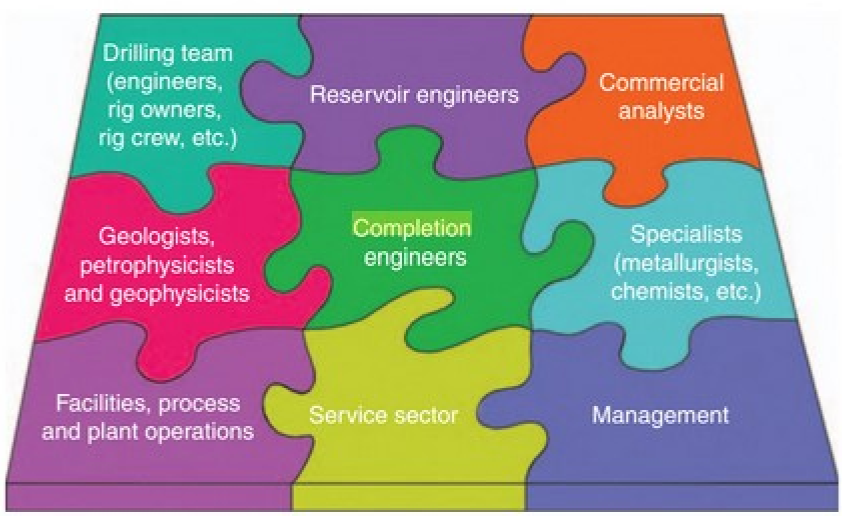
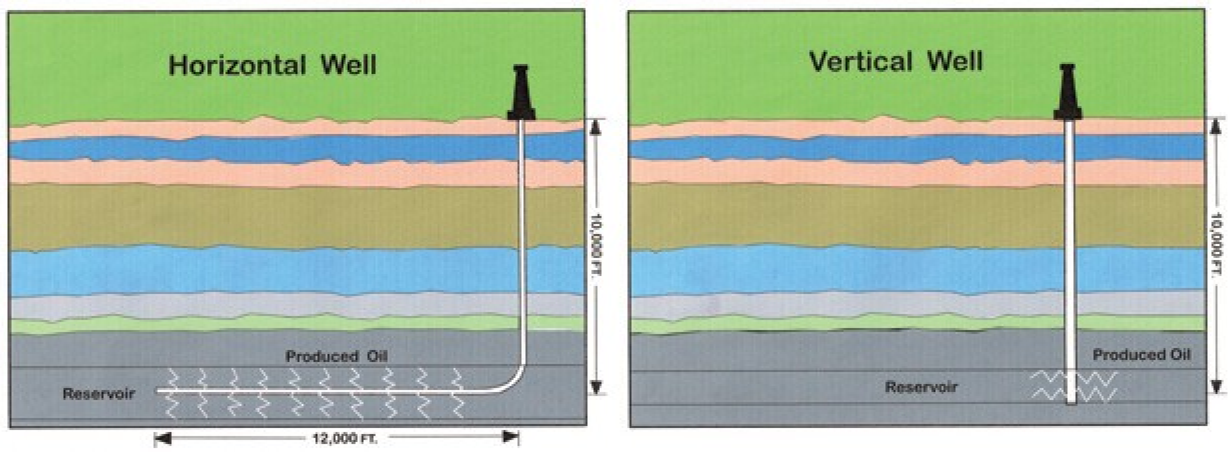


Figure 1. 1 The role of completion engineers (Jonathan, 2009)

The well completion method selected can directly influence wells' productivity, stability and longevity, which has important effect on economic benefit of oilfield development. Making inappropriate decision on well completion method not only can lead to serious damage and pollution on reservoir, but also can result in inactive well or dramatically reduce the productivity, which are all heavy losses for oil companies. Typically, there are trade-offs among benefits. For example, with certain designs leading to lower costs and others leading to more productivity or less risks [2]. MODM and MADM are very useful methods to deal with this kind of situation, they can handle both quantitative as well as qualitative criteria and analyze conflict in criteria and decision makers [3], they can also assess trade-offs between multiple criteria or objectives in order to rank, prioritize or choose within alternatives.

Generally, there are two kinds of wells: vertical wells and horizontal wells, which are suitable for different kinds of reservoirs, as shown in Figure 1.2 (Michael, 2016). The major purpose of a horizontal well is to enhance reservoir contact and thereby enhance well productivity [4], it is very useful for fractured oil reservoir, the recovery of residual oil and heavy oil .Well completion technologies have had big development for both vertical and horizontal wells in recent years, from single perforated completion method to a set of comprehensive technologies that can protect strata, enhance productivity and recovery ratio. Well completion methods can mainly be divided into five types: open hole, perforated completion, slotted liner completion, gravel packing completion and EPC completion, which will be described in detail in chapter 3. These five basic completion methods can be combined at random, like in 1998, Baker Oil Tools company [5] finished a large displacement well to exploit heavy oil in shallow strata by combining open hole and gravel packing completion method. Texaco company also applied this completion method on North Buzachi oilfield in 2000 to prevent sanding [6]. Schlumberger and Baker-Hughes company completed a batch of oil wells in Gulf of Mexico successfully by using wire-wrapped screen combined with gravel packing completion [7]. A so-called intelligent completion system is a new and advanced technology, and it was introduced into oil and gas industry in the mid 1990s [8]. This system usually consists of permanent downhole sensors and surface controlled downhole flow control valves, which can provide real time zonal downhole monitoring of pressures and temperatures. It can also realize real time production management by controlling switches and valves in different layers. Although intelligent completion system has many benefits, there are various challenges involved in the design and implementation of this system for field development [9]. These challenges include downhole completion barriers [10], much more complex technology than conventional methods, much higher initial expenditure and operation cost, control and monitor objectives [9], data management [11], etc.



(a) Horizontal well (b) Vertical well

Figure 1. 2 Comparison of horizontal well and vertical well (Michael, 2016)

However, influenced by technology and skill, a lot of oil fields and companies often put more focus on proficiency than adaptability, which causes about 90 percent of well completion methods are perforated completion. This is not a promising phenomenon and can hurdle productivity and recovery ratio's enhancement, so a systematic selection system for well completion methods is necessary.

1.2 Research Motivation

Wellbore provides the only path from surface to reservoir, so well completion is an important influence factor for ultimate reserve capability of a well. To a large extent, the successful production and depletion of a reservoir depends upon the successful completion. Therefore, the selection of well completion methods is a crucial part for oil companies. Based on the research after of this thesis, all the commonly used well completion selection models and methods reported so far are not balanced. Some of them only depend on experts' knowledge, experience and judgement, which are too subjective and cannot cover all the aspects needed to be considered during the selection. Others only depend on numerical indexes, like initial production, operation cost etc., which ignore experts' input and are too idealized. In addition, almost all those reported evaluation systems are too superficial and only include cost criteria, production criteria, time criteria and risk criteria, which cannot evaluate well completion system comprehensively.

Therefore, the well completion selection system deserves extensive study and further exploration to get improvement.

Furthermore, the selection of well completion is a very complex engineering procedure, which is influenced by lots of different factors, so it has been hard to address the problem by using conventional crisp deterministic decision- making methods. Hence, this research explores to adopt a uncertain system, like fuzzy MODM or MADM methods. Although some researchers have applied AHP on well completion selection system, there is no fuzzy AHP has been adopted in this domain yet.

1.3 Objective and research contributions

The objective of this measure is to build a reasonable and comprehensive optimum selection system, and this system can lay a solid foundation for future research. This thesis focuses selecting the optimum well completion methods for different reservoirs. In essence, the selection system supports a practice process of transforming human being's subjective list of requirements into a more objective model of reality. This process involves engineering analysis, assumption, comparison, selection and optimization, so it is a decision-making activity. Because everyone has different view, opinion and knowledge structure, so different people may come up with different well completion methods for one reservoir. This research builds a system that can integrate both objective indexes and subjective judgements. Therefore, this system aims not only to satisfy the basic requirements for well completion, but also can meet different needs arising from different companies and oilfields.

The main contributions expected from this thesis are summarized as follows:

- A review of many research works related to optimum selection of well completion methods. The strengths and weakness of these methods are summarized and commented, which can provide meaningful foundation of research as well as a resource of information for further research.

- Propose the framework of a feature-based integrated well completion selection system, and build a corresponding optimum decision-making model, which can be applied to both vertical and horizontal wells.
- Propose a new characteristic data structure representing the common selection considerations in the form of an associated object class, called well completion method feature, which not only can coordinate different expert areas to describe this complex decision-making process, but also can capture essential demands into a tree of engineering entities and then avoid rework and iterations. In addition, using the feature modelling approach can bring all those separate models together to describe the full system in a coordinated and comprehensive way. Therefore, it is expected that this system can be expanded easily to include new models.
- Develop five primary evaluation models: reservoir failure mode identification, stimulation technology determination, productivity, cost and HSE model. Each of these models has its own corresponding second level criteria. Based on my research, there is no well completion selection system has ever considered HSE and stimulation technology demand before.
- Introduce a risk assessment method into evaluation system to improve safety and reliability of finial decisions, which can also save time of doing risk assessment independently.
- Combine MADM and MODM into one system, which can solve complex problems with multiple influence factors in a more versatile approach.
- There are a lot of determined variables exist in the selection decision-making process, however, in previous studies, almost all inputs are crisp deterministic numbers when determining weights. This thesis adopts fuzzy AHP to determine weights. This approach can better deal with problems under ambiguous surrounding.
- Set up a new pairwise comparison scale for AHP, which is more suitable for fuzzy AHP's judgement.
- Modify and improve the way to do AHP's consistency check. The conventional way to measure the consistency of pairwise comparison judgment is by computing a consistency ration. The ratio is designed in such a way that values of the ratio exceeding 0.1 are indicative of inconsistent judgments. However, the number 0.1 is got just based on experience, lots of researchers have raised doubts for that. Therefore, I have put up with a

new method to check judgment matrix's consistency, which will be introduced in the following chapters.

- The selection system proposed by this thesis is very flexible. This system can meet different reservoirs' needs and companies' requirements based on their own conditions by adjusting weights, which has extensive applicability.
- Both subjective and objective MCDM methods have their own pros and cons, so the proposed system combines Fuzzy AHP and entropy method together to achieve complementation, so the final weight is more scientific, more accurate and reasonable.
- Complete a well completion methods optimum selection software based on C#.

1.4 Thesis organization

This thesis is organized into nine chapters which are briefly described here after.

- **Chapter 1** – Introduction

  This chapter introduces the background, research motivation, objective and the contribution of the thesis. The thesis organization is structured in this chapter here.

- **Chapter 2** – Literature review

  Literature related to MCDM and its application in oil industry is presented and discussed in this chapter.

- **Chapter 3** – Fundamental knowledge

  This chapter presents the basic knowledge of well completion methods, including their applicable conditions, advantages and disadvantages. The basic knowledge of feature theory is also described.

- **Chapter 4** – Determination and quantification of evaluation modules

  This chapter introduces the evaluation modules in the selection system. All the qualitative indexes are quantified.

- **Chapter 5** – Feature-based optimum selection of well completion method

This chapter represents framework of well completion selection system in UML, and the newly proposed weight determination method is also discussed in this chapter.

- **Chapter 6** – Case study 1-heavy oil extraction in Christina Lake

  A horizontal well in heavy oil reservoir is used in this chapter to demonstrate the usability of this system.

- **Chapter 7** – Case study 2-light oil production in He 50

  A vertical well in light oil reservoir is used in this chapter to demonstrate the usability of this system.

- **Chapter 8** – Development of a well completion method optimal selection software prototype

  This chapter introduces a software based on the proposed selection system.

- **Chapter 9** – Conclusion and future work

  This chapter states conclusions, and suggested future work is also presented.

Chapter 2: Literature review

In this chapter, literature related to decision-making methods and its application in oil industry is discussed. Particularly, MCDM methods are very much focused in Section 2.1, because they are particularly relevant to this research methodology. MCDM is the abbreviation of “multi-criteria decision-making”. It is an important part of modern scientific decision-making theory. A number of MCDM methods have been applied in oil industry, like making selection of well completion methods, selecting proper candidate wells for hydraulic fracturing treatment, etc. they will be reviewed in Section 2.2, and each of these applications’ strengths and weaknesses are to be discussed. Finally, the literature review is summarized in Section 2.3.

2.1 Review on decision making methods

Every organization needs to make some decisions to achieve its goals, and the decision maker has to ensure the final decision is a reasonable choice among alternatives. Decision makers can be managers at various levels, from an engineering project manager to a CEO of a large company, and their decision problems can be various [12]. Decision making quality is essential due to the fact that cost of making errors can be very large and the chain reaction that an error can cause trouble in many aspects [12]. Furthermore, there are lots of influence factors affecting a decision, so is the body of knowledge from various disciplines. Because of the above reasons, technical support for decision making is necessary and yet challenging.

Decision problems can be classified based on a given problem structure: structured, semi-structured, or unstructured, the latter two are also called ill-structured [12] Structured problems can be described by existing classic mathematical models and can be solved by standard solution methods [13]. Fuzziness is an important character for unstructured problem and they usually cannot be solved by existing standard methods. Semi-structured problems have characters from both structured and unstructured problems, so the commonly used strategy to deal with them is to combine both a standard solution and human judgement. It can be appreciated that it is hard to get a satisfactory decision for choosing an appropriate well completion method, because this problem is a semi-structured and yet a multi-criteria decision-making problem.

2.1.1 Multi-criteria decision making

Decisions involving multiple criteria are very common but difficult to make. The Multi-Criteria Decision Making (MCDM) method has been found a useful to deal with semi-structured problem. It is a branch of operation research models and is also a well-known part in decision-making field. This method can handle both quantitative and qualitative criteria, and can analyze conflicts among criteria [14]. In addition, it can assess trade-offs between multiple criteria and objectives to better rank, prioritize and make choice. The typical process of MCDM is shown in Figure 2.1. The origin of MCDM can be traced back to 1896 when Pareto put forward the Pareto optimality-based concept [15]. Then Koopmans introduced the concept of efficient point to decision-making field in 1951 [16] and in the same year, Kuhn and Tucker proposed the concept of vector optimization [17]. MCDM did not become a normative method in decision-making field until Charnes and Cooper did research on objective programming [18] and the ELECTRE method proposed by Roy in the 1960s [19]. The decision made by MCDM is not the “best” one that can satisfy every objective but can help decision makers choose an alternative that can fit their needs.

All multi-criteria decision problems share the following common characteristics [20]:

- Criteria are non-commensurable, which means there is no unified measuring standard or unit of measurement in these criteria, so they are hard to be compared.
- Contradictoriness exists within multi objectives, which means it is very hard to get a decision that can optimize every single objective at the same time.
- Both quantitative and qualitative criteria are needed to be considered.

These characters make the difference between single-criteria and multi-criteria decision. Hence some special methods are needed for multi-criteria decision making. In general, such methods can be divided into two categories: multi-objective decision-making (MODM) and multi-attribute decision-making (MADM). In MODM, the decision problem is characterized by the existence of multiple and competitive objectives that should be optimized against a set of feasible and available constraints [21] rather than, as in MADM, the evaluation of a set of alternatives against a set of criteria [14]. Methods for MODM and MADM will be described in detail in the next two sections.

MCDM solution methods can be divided into three categories [22]:

- Unique synthesis criterion approach: It consists of aggregating the different points of view into a unique function which will be optimized [23]. Both Analytic Hierarchy Process and Technique for Order of Preference by Similarity to Ideal Solution(TOPSIS) belong to this category.
- Outranking synthesis approach: This type method can represent decision makers' preference by a relationship called outranking relationship. Elimination and Choice Expressing Reality (ELECTRE) and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) belong to this category.

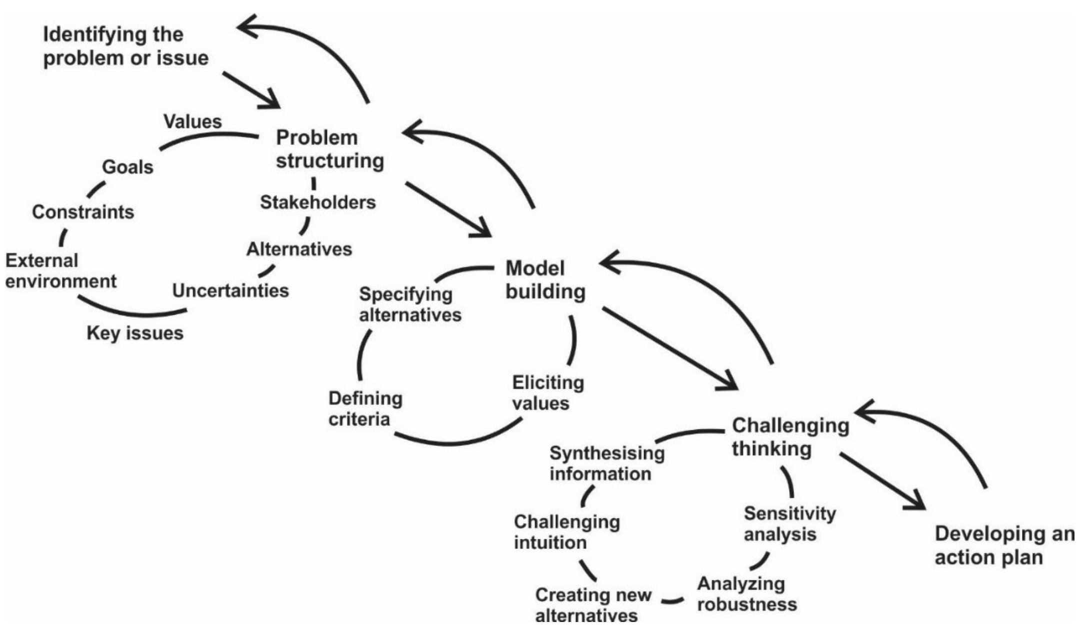


Figure 2. 1 Typical process of MCDM (Belton & Stewart, 2002)

- Interactive local judgement approach: This proposes methods which alternate calculation steps, giving successive compromising solutions, and dialog steps, leading to an extra source of information on decision makers' preference [23].

2.1.2 Multi-objective decision-making

There is always an ideal solution exists for single-objective decision-making (SODM) problem, but rarely there is a unique superior solution for a MODM problem. There are four kinds of solutions for MODM problems: absolute optimal solution, inferior solution, Pareto-optimal solution and weak Pareto-optimal solution. In addition, there are three types of relationship between solution A and solution B for SODM: A<B, A=B, A>B; but for MODM, there is one more "incomparable" relationship [24]. Furthermore, MODM can present the preference of decision makers, which SODM cannot. Because of these differences, MODM is much more suitable to solve objective and realistic problems than SODM.

As mentioned above, specialists have proposed different kinds of MODM method to deal with realistic issues. Some useful methods are introduced in the next section with and both their advantages and disadvantages.

a. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS was originally developed by Hwang and Yoon in 1981 [25] with further developments by Yoon in 1987 [26], and Hwang, Lai and Liu in 1993 [27]. TOPSIS is an effective method for MODM problems, it can rank limited alternatives by calculating the geometric distance between alternatives and ideal solution. There are two kinds of ideal solution, one is called positive ideal solution(PIS), which can optimize every attribute value, and the other one is called negative ideal solution(NIS), which is the most unsatisfied solution for every attribute value. The basic concept of TOPSIS is choosing the alternative that has the shortest geometric distance from the PIS and the longest geometric distance from the NIS [28]. TOPSIS is a compensatory method, which means there are trade-offs among criteria, so a good result in one criterion can compensate a bad result in another criterion [29], it is better than non-compensatory methods when dealing with realistic problems.

Advantages of TOPSIS [30]:

- TOSPSIS has no strict restriction for sample size and data distribution, it can be applied on both small size sample analysis and large size sample with multi-index;

- Original data can be fully used, which can reduce the loss of original information;
- A sound logic that represents the rationale of human choice;
- Simple computation process;
- The performance measures of all alternatives on attributes can be visualized on a polyhedron, at least for any two dimensions.

Disadvantages of TOPSIS:

- TOPSIS presents the problem of ranking reversal, which means the final ranking can swap when new alternatives are included in the model;
- It is hard to get PIS and NIS when the normalized matrix is complex;
- Alternatives cannot be compared with each other when they are symmetrical about the line formed by PIS and NIS.

b. Elimination and Choice Expressing the Reality (ELECTRE)

The acronym ELECTRE stands for Elimination and Choice Expressing the Reality [31] . The first ELECTRE method was proposed by Benayoun, Roy and Sussman (1966) [19], then other ELECTRE methods were developed during next few decades: ELECTRE II (Roy&Bertier,1971) [32], ELECTRE III (Roy,1977) [32], ELECTRE IV (Roy&Hugonnard,1981) [32], ELECTRE TRI (Yu,1992; Roy&Bouyssou,1993) [33] and ELECTREIS (Roy& Bouyssou, 1993) [33]. Different versions of ELECTRE methods are used to deal with different kinds of problems, and those problems can be divided into three types: choice problematic, ranking problematic and sorting problematic [34]. ELECTRE I, IV and IS can be used to handle the choice problematic, which the objective is to select a smallest set of best alternatives. Ranking problematic is concerned with the ranking all the alternatives from the best to the worst, and ELECTRE II, III, IV are usually used to deal with this kind of problem. A set of categories must be priori defined for the sorting problematic, and the objective for this kind of problem is to assign all alternatives to the pre-defined categories which are defined by norms or typical elements of the categories [35], and ELECTRE TRI method is designed to handle this kind of problem. There are two important concepts in ELECTRE approach: outranking relation and thresholds.

ELECTRE method introduces a new concept called indifference threshold, which is specified by decision makers. While the introduction of this threshold goes some way toward incorporating how a decision maker actually feel about realistic comparisons, a problem remains[36]. Another threshold is called preference threshold, which is a buffer zone between indifference and strict preference [36].

ELECTRE methods comprise two main procedures: the first is building outranking relations, the second is called exploitation procedure [35]. The objective of the first step is to compare each pair of alternatives in a comprehensive way, the exploitation procedure is used to elaborate recommendations from the result obtained in the first step [37] .

Advantages of ELECTRE method:

- ELECTRE methods can be used to discard some inferior alternatives before applying another MODM methods, which can save much time;
- Outranking methods can take account purely without converting the original scales into abstract ones with an arbitrary imposed range, which can keep the original concrete verbal meaning [38];
- ELECTRE methods contain two parameters: indifference and preference thresholds, they are useful when modeling the imperfect knowledge of data [39];
- ELECTRE methods can be used to deal with both quantitative and qualitative judgements.

Disadvantages of ELECTRE method:

- ELECTRE methods need lots of primary data, which is much more complex than other methods [40];
- ELECTRE evaluates a criterion even if it has a weight equal to zero [41].

c. Multi Objective Programming Approach (MOPA)

MOPA was proposed by A. Charnes and W.W. Cooper in 1957 [42], then developed by U. Jaashelainen and Sang. Leethe [43], they gave a general method for goal programming problems called simplex method. The basic thought for MOPA is giving expected values to every objective function and finding the closest solution to target expected value under certain constrains. Not all objectives can be achieved because of constrains, so positive and negative deviation variable are introduced to represent deviation between expected values and actual values. The final objective of MOPA method is to transform multi-objective problems into single-objective problems.

Advantages of MOPA method:

- MOPA can change “hard constrains” into “soft constrains”, “hard constrains” means the constrains must be satisfied, “soft constrains” do not need to be satisfied totally and can be violated to some extent, which can make solutions always be available even though constrains are contradict with each other;
- The importance of objectives can be distinguished by priority factor, and weight coefficient can be used to rank objectives with the same priority factor;
- One objective can be optimized while constraining the others to be no worse than specified values.

Disadvantages of MOPA method:

- MOPA can only solve problems which objectives and constrains are liner functions;
- Because of fuzzification, some objectives, constrains and coefficients cannot be clearly represented by functions.

d. Entropy method

Entropy was firstly appeared in thermodynamic, and was introduced into the decision-making system by Shannon in 1948 [44], and has had widely applications in many fields. Information entropy is the measurement of disorder degree of a system [45], high disorder degree means high entropy, vice versa. For one index, more information means less uncertainty and smaller entropy, so a higher weight should be given to this index. On the other hand, if the entropy is high, then this index should get a small weight, because it indicates this index can only provide very little useful information to the whole system. In conclusion, entropy weighting method is an objective method and barely can be affected by human beings’ judgement.

The step of entropy method is shown as follows:

1. Form original index data matrix
2. Apply dimensionless method to the data matrix
3. Calculate index's weight of every evaluation object
4. Determine entropy of each index
5. Determine variation coefficient of each index
6. Calculate entropy weight of each index

Advantages of entropy method:

- Entropy-based method is an objective weighting get method, so it can get unbiased relative weights for criteria [46];
- Entropy can identify both contrast intensity and conflict of criteria;
- Entropy method permits a quantitative assessment of efficiency and benefit/cost parameters [46];
- Entropy method can represent and reflect criteria's discrimination;
- Entropy method can better handle the inherent conflict between criteria, because it can produce more divergent coefficient values for all criteria [47].

Disadvantages of entropy method:

- The weight may get distorted without any expert judgement;
- Entropy method does not consider the mutual relationship between criteria, there is no horizontal comparison between them;
- Entropy method is related to proper problem sizing, i.e. preserving that the decision matrix contains sufficiently large set of alternatives [48].

e. Analytic Hierarchy Process (AHP)

AHP is developed by Thomas Saaty in the 1970s, which is a useful method to deal with complex, irreversible decision-making problems. The basic idea behind AHP is to convert subjective assessments of relative importance into a set of overall scores and weights [49]. AHP decomposes problems into hierarchies and compare factors in pairs to form a comparison matrix, and this is a distinguishing characteristic of AHP. The pairwise comparison is often regarded as straightforward, intuitive and convenient means to extract subjective information from decision makers concerning their implicit preferences [50]. However, inconsistency may arise in AHP when the logic of preferences is applied. For example, there are three alternatives 1, 2, 3, 1 is preferred over 2, and 2 is preferred over 3, inconsistency means 1 may not be preferred over 3.

The AHP process is carried out as follows:

1. Set up hierarchical structure: In MODM, AHP usually decomposes the decision problem into three layers (Figure 2.2), descending from an overall goal to criterial and alternatives, in successive levels [50], more complicated problems may exist on sub-criteria layers. The top goal layer is the final objective that decision makers want to achieve; criterial layer targets on those sub-goals that needed to be considered when evaluate alternatives; alternative layer includes all available alternatives.

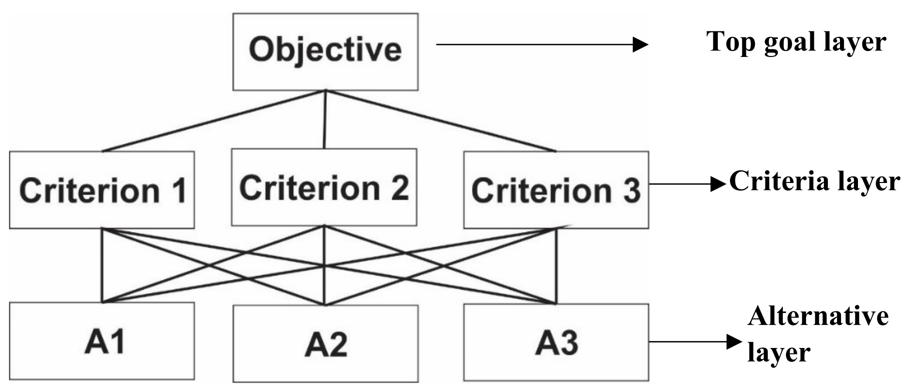


Figure 2. 2 AHP's hierarchical structure for MODM

2. Use paired comparisons to build judgement matrix: For example, for criterion H, the lower layer includes alternatives A1, A2, …, An, then judgement matrix for H is:

H	A_1	A_2	…	A_j	…	A_n
A_1	a_{11}	a_{12}	…	a_{1j}	…	a_{1n}
A_2	a_{21}	a_{22}	…	a_{2j}	…	a_{2n}
…	…	…	…	…	…	…
A_i	a_{i1}	a_{i2}	…	a_{ij}	…	a_{in}
…	…	…	…	…	…	
A_n	a_{n1}	a_{n2}	…	a_{nj}	…	a_{nn}

$$A=\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (2.1)$$

The importance factor matrix A is a $n \times n$ real matrix, where n is the number of evaluation criteria considered, each entry $a_{ij}$of the matrix A represent the importance of the i_{th}criterion relative to the jth criterion [51]. For example, for criterion H, the weights for A_1, A_2, …, An are w_1, w_2, …, w_n, then $a_{ij} = \frac{w_i}{w_j}$, and the entries a_{ij} and a_{ji} satisfy the following constraints:

$$a_{ij} > 0 \quad (2.2)$$

$$a_{ij} * a_{ji} = 1 \quad (2.3)$$

$$a_{ij} = 1 \quad (2.4)$$

3. Define judgement scale: The most common used scale of measurement for AHP is called one to nine ranking scale method which is proposed by Satty (1990). This ranking method is shown in Table 2.1 [52].

Table 2. 1 Table of relative scores

Value of a_{ij}	Definition	Explanation
1	Equal importance	i and j re equally important
3	Weak importance	j is slightly more important than i
5	Essential importance	j is more important than i
7	Very importance	j is strongly more important than i
9	Absolute importance	j is absolutely more important than i
2, 4, 6, 8	Intermediate values	Intermediate values to reflect compromise

4. Single hierarchical arrangement: This step will get the largest eigenvalue λ_{max} and the corresponding eigenvector. There are several ways to get λ_{max}, like square root method, sum-product method etc.
5. Checking the consistency: As mentioned before, some inconsistencies may typically arise in judgement matrix, so it is necessary to check consistency. Satty gave a measure of consistency, called Consistency Index as deviation or degree of consistency using the following formula [53]:

$$\text{CI} = \frac{\lambda_{max} - n}{n - 1} \tag{2.5}$$

   Knowing the Consistency Index, the next step is comparing it with Random Consistency Index (RI), shown in Table 2. Then, Satty proposed what is called Consistency Ratio (CR), which is a comparison between Consistency Index (CI) and Random Consistency Index (RI), or in formula [53]:

$$\text{CR} = CI/RI \tag{2.6}$$

Table 2. 2 Random Consistency Index

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

   If CR is smaller or equal to 0.1, the inconsistency is acceptable. If CR is larger than 10%, then the judgement matrix needed to be revised.
6. Overall hierarchical arrangement: Calculating the total weight for every alternative and ranking.

Advantages of AHP method:

- AHP can deal with both qualitative and quantitative evaluations;
- AHP can capture both subjective and objective evaluation measures;
- AHP is simple because no complex expert system needed to be built in it [53];
- AHP is more flexible than other MCDM methods, it equip with the ability to check inconsistencies [54];

- AHP can decompose decision problems into its constituent parts and builds hierarchies of criteria to make pairwise comparison easier [55];
- AHP can support group decision-making through consensus by calculating the geometric mean of the individual pairwise comparisons [56];
- AHP is equipped with clear and auditable hierarchical framework, which can clearly show the relationships between different layers and it is easy to define top strategic objectives and specific metrics to better deal with decision-making problems;
- Personal perspectives can be combined with scientific process in AHP method.

Disadvantages of AHP method:

- AHP may require a large number of evaluations by decision makers for problems with many criteria and options;
- The most commonly used 1 to 9 scale method can often cause inconsistencies and it is often difficult to distinguish among them;
- Rank reversal is not an uncommon problem exists in AHP, this problem occurs when new alternatives are added into;
- It is often hard to pass consistency test if a lot of criteria are needed to be considered;
- AHP has an important assumption, that elements should be independent with each other, however, it is hard to control when dealing with practical problems;
- AHP can only choose the best one from existed alternatives, it cannot generate a better new method.

2.1.3 Multi-attribute decision-making

MADM problems can be described as the following: Given a group of alternatives, each alternative will be evaluated according to multiple attributes, the objective of MADM is finding the most satisfied alternatives to decision makers. MADM is an important theory and a method which has been widely applied in social, economic and management fields. Churchman et al. (1957) [57] were the earliest people who dealt with a MADM problem by using simple additive weighting method, then MacCrimmon (1968) [58] wrote a review about MADM's methods and application.

Hwang and Yoon published a book about MADM in 1980s [58], which includes 495 papers and they classified 17 methods based on whether attributes are known or unknown.

a. Analytic Hierarchy Process(AHP)

The process of AHP method for MADM problems is very similar with AHP for MODM problems, but the hierarchical structure is different, shown in Figure 2.3.

b. Preference ranking organization method for enrichment(PROMETHEE)

PROMETHEE is proposed by Brans (1982) and further extended by Vincke and Brans in 1985 [59]. PROMETHEE is an outranking method for a finite set of alternative actions to be ranked [60]. The PROMETHEE family includes the PROMETHEE I for partial ranking of the alternatives and the PROMETHEE II for complete ranking of the alternatives [60], then some other versions of the PROMETHEE methods were developed to deal with more complex decision-making problems.

Advantages of PROMETHEE method:

- PROMETHEE has more stability than ELECTRE method and has lower probability for reverse ranking;
- PROMETHEE method does not need to nondimensionalize and normalize indexes, which avoid information deviations;
- PROMETHEE can deal with uncertain and fuzzy information;
- PROMETHEE can simultaneously deal with qualitative and quantitative criteria. Criteria scores can be expressed in their own units [61].

Disadvantages of PROMETHEE method:

- PROMETHEE does not give method for how to determine weight, which need decision makers to decide how to generate weights, it is a hard job for decision makers who lack of experience;
- PROMETHEE does not have a structured analysis as good as AHP;
- Although the probability is not as high as other methods, PROMETHEE still may suffer from the rank reversal problem;

- The way in which the preference information is processed is complicated and hard to explain to non−specialists [62].

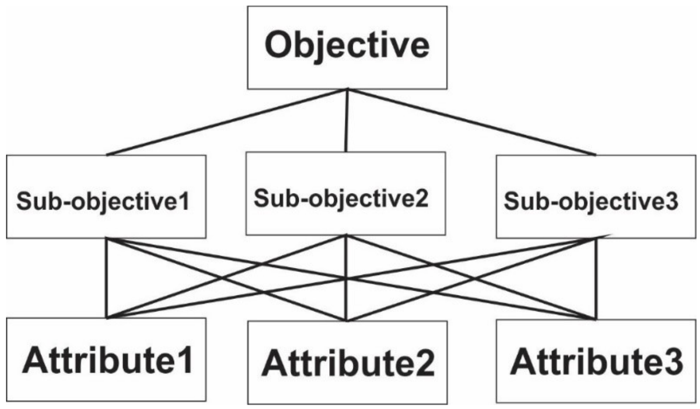


Figure 2. 3 AHP's hierarchical structure for MADM

c. Grey relational analysis (GRA)

GRA was proposed by Deng [63] so it is also called Deng's gray incidence analysis model, which is part of grey system theory. GRA is an efficient method to deal with decision-making with incomplete and uncertain information. The most special character of GRA is the way it defines information. It defines situations with no information as black, and those with perfect information as white. However, neither of these ever exists when deal with real problems, so the grey system defines situations between these two extremes as grey information [64]. Then a continuum is formed from unknown information to known information, which means from black through grey to white [64]. As for system solutions, no solution can be derived from situations with black information, because there is no information available; a unique solution could be gotten from a system with white information; grey systems can give a variety of available solutions. GRA solves MADM problems by combining all attributes values into one value, which can transform the original multi-attribute problem into single-attribute problem.

More details about GRA calculation can be found from Kuo, Y., Yang, T., & Huang, G. W (2008) [65]

Advantages of GRA method can be summarized as follows:

- GRA method is based on original data and there is no complicated calculation included in it;
- GRA method can deal with the MADM problems with insufficient information;
- GRA method can determine the overall index without consulting utility function.

Disadvantages of GRA method are that:

- GRA method needs to determine optimal values for each index, the subjectivity is too strong, and some optimal values may hard to determined;
- GRA method cannot reflect the situation relationship between an alternative and the idea alternatives.

2.2 Review of decision making process in oil industry

Well completion engineering is an important link in petroleum industry, and selection of well completion method is a crucial part of well completion engineering. Well completion method can influence the whole process of exploitation and has direct relationship with production, so it is necessary to find a proper way to select a matching completion method for a well.

Nowadays in oil industry, the most commonly method to select well completion method is making decisions based on experience and knowledgeable experts.

Johnston et al. (2008) [66] suggested that the selection of the best completion method for a well is a multi-disciplinary problem, which needs knowledge from geology, chemistry, petroleum engineering, geophysics etc., so the authors in their paper tried to integrate opinions from different fields to select a suitable well completion method for a specific formation.

Jia et al. (2016) [67] chose optimum completion method for a specific gas reservoir, although authors analysed the reservoir's situation in detail and built corresponding geological model, the way they used to determine the well completion method is still too rough. They did not consider the weight of different influence factors and just made decision based on experience. In conclusion, selecting well completion method based on experience is lack of veracity and systematization.

Idiodemise et al. (2007) [68] proposed a set of selection criteria for well drilling and completion, like well selection, junction selection, sand completion selection etc. Authors used criteria they set to make choice, which is a simple and clear way. However, a selection may include several influence factors which can result in contradiction. For instance, there are many factors needed to be considered when decide whether a sand-control device is needed or not, for factor 1 this device is needed, whereas for factor 2 no sand-control device is needed, which are contradicting with each other. Therefore, weight is a necessary component to avoid contradiction.

Some researchers have tried to propose a systematic methodology for well completion method selection, so several research efforts are focusing on the development of flow chart. The overall goal is to build a selection system, which has procedures and steps can be followed.

Ouyang et al. (2006) [69] developed an eight-step flow chart to select a cost efficient yet production and sand, gas, water control effective completion method for wells. The authors proposed the well completion cost can be divided into two parts, intangible well cost and tangible well cost and they also concluded items included in these two categories. However, this flow chart is too general and is hard to be applied in the real field. In addition, predictions of wells' performance (like production, the pressure drawdown etc.) are all depend on a commercial software, which is not convenient for companies do not have access to this software or people who do not how to use this software. Furthermore, although estimated cost for each well completion method was given in the example and the cost was used as a restrictive factor to select well completion methods, authors made the final decision too subjectively and did not give enough evidence and explanations.

Sinha et al. (2003) [70] did a field survey (including 48 cases) to assess the relationship between well architecture and reservoir characteristics, and they concluded some certain common attributes for different field environment (land, platform and subsea fields). Authors broke the whole well architecture into three basic parts, which are well trajectory, formation completion, and key completion equipment. A set of flow charts were developed to select these three parts, which are based on common attributes they got from case histories. However, almost all selections in those flow charts are qualitative analyses from experience, which is too subjective and not accurate enough. The good part is the authors decoupled the well design problem into a high-level or conceptual design phase and a detailed design phase, and allowed for iterations between two, which can effectively convert the inflow stream from the reservoir to the outflow stream that can be handled by surface infrastructure.

Garrouch et al. (2003) [71] developed the selection of multilateral schemes, lateral-section completion equipment and junction-level respectively and integrated these three parts to develop an integrated completion-planning approach, which are all based on the current global and broad experience attained in field. Flow chart was applied to show their work, advantages of this flow chart is it has clear and logical structure, which can be easily described, however, at the same time, it has some uncertainties and it is hard to identify the clear bound, both the input and output in the flow chart cannot be modeled, so it is easy to lose some detailed information.

Well completion method selection is a multi-objectives and multi-attribute problem, and since there are many limitations using flow chart to deal with this kind of problem, some researchers applied MCDM methods in oil industry's selection.

Morooka et al. (2002) [72] proposed a methodology based on Theory of Utility Function and Multi-attributes concept to select the best floating production system. This method considered technological, safety, environmental risk and the financial factors. The disadvantage of this method is it is hard to determine the correct model of utility function for each factor considered in this paper, so environment risk and technological risk are determined qualitatively, which is not accurate enough. The other point is the author did not consider the variation of weighting functions.

Rehman et al. (2002) [73] used a distance-based optimization model, which coupled integrated production simulations, economic analysis to improve the selection of lifting option for gas wells. The final decision is determined by the composite distance between alternative and optimum case, which means the smaller this numerical value is, the better this alternative is. This approach does not have very complex mathematical calculation, so it is simple and feasible. However, authors did not mention how to determine the optimum value for each attribute, and the optimal criteria can be different under different situation. In addition, the production system was modeled with a commercial software package, so the feasibility of integrating this software with the distance-based optimization methodology needed to be considered.

Yang et al. (2013) [74] paper used Fuzzy synthesis decision-making method, Grey system theory and TOPSIS method to select an appropriate well completion method of coal-bed methane for a specific place. The good aspect is it considered both production and economic benefit, and the way it determined weights (combined Entropy Theory and Deviation Maximization Method) is not too subjective. However, there are some points need to be improved. For example, the way to determine evaluation indexes is too rough and authors did not describe the way they used to combine the three MODM method clearly, which means although they have used three different methods, they did not couple with each other in a convincing way.

Ataallahi et al. (2015) [75] applied fuzzy logic in HSE management in oil industry, which is a new attempt.

Based on the analysis of different MADM and MODM methods, AHP is the best method to deal with well completion method selection problem, and some researchers have tried to apply AHP in oil industry.

Mehrgini et al. (2014) [76] tried to select proper candidate well for hydraulic fracturing treatment. This study recognized 14 effective parameters by meeting with experts and AHP method was applied to determine the quantitative weight of each parameter. However, all feasible parameters were determined based on experience, which did not use the advantage of MADM method completely. In addition, authors used the non-fuzzy method, which exists the uncertainty of human preference.

Keivanpour et al. (2014) [77] used combination of AHP and social choice theory to achieve an optimum production profile. The social choice theory they used is called Borda count method, which is a committee-style voting process. Authors considered both technical limitations and unreliability of economic assumptions. However, they did not consider the technical parameters for the different reservoir characteristics and they did not solve the uncertainty of human preference. Besides this study, AHP plus social choice theory were also used by Srdjevic et al. (2007) [78] in water management. This study compared two methods of group decision-making, the first was based on AHP only and two group aggregation techniques, the second used AHP in subgroups and used social choice methods in the group level and aggregation. The advantage of the combination of AHP and SC is it gives a chance to individual groups to expose their choices in a more explicit and democratic way and it is better for adaptation in real life decision-making. However, this method only uses partial information, or does not use all the available information at one time, which can lead to different outcomes when using different voting methods (i.e. The Hare system, Pairwise comparison voting, Approval voting, The Borda count).

Pourafshary et al. (2009) [79] applied AHP method successfully in the priority assessment of investment in development of nanotechnology in upstream oil industry, which got the conclusion that technologies related to enhanced oil recovery are the most attractive one to apply nanotechnology.

Fu et al. (2011) [80] used AHP to establish the hierarchical structure of influence factors in drilling and completion methods, the objective is to rank the priority of these factors. All factors are classified into geometric parameters and physical parameters. The weighting of parameters on selection is calculated by counting the occurrence frequency of the parameters in literatures. Then authors concluded a flow chart to select the best well completion method based on the priority of those influence factors, so AHP method was only used on ranking influence factors, but not on the selection of well completion methods. In addition, the way to determine weights of criteria is based on occurrence frequency in literature, which is not accurate enough.

Khosravanian et al. (2016) [2] used two MCDM methods - AHP and TOPSIS to select the appropriate well completion design, which was applied on three high-rate gas well completion alternatives- mono bore(MB), big bore(BB) and optimized big bore(OBB). The criteria considered in this study contained time to run the completion, capital and operating costs, gas production rate achieved and risk exposure associated with every well completion method. Authors divided the whole system into two levels, the technical level and the strategic level respectively and conducted sensitivity analysis to demonstrate that making changes in weights at either of those two level is likely to yield different outcomes. The strength of this study is it applied MCDM methods on the selection of well completion, so the key criteria variations for the alternatives considered can be described in linguistic terms converted and then converted to semi-quantitative scores, or expressed in actual values of measured units, which can help expert teams to reach consensus on the semi-quantitative and quantitative scores and values to ultimately be applied to specific decisions. The other advantage is this study enables to can get different ranking of priorities by adjusting weights putting on each criterion. For example, one company has enough money so all it cares is production, then you can put more weights on production in this system. However, there are still some points needed to be improved. First, authors have already chosen three well completion methods based on some requirements before using the system provided in this paper, which means users need to narrow the scope by themselves first and then this system can be applied. Therefore, this system is not accurate enough to be applied on larger selection scope so far. Secondly, the weights used in this system are all given by experts, which is affected by subjective factors too much. Thirdly, although authors used both AHP and TOPSIS in this paper, they used them separately to get two methods to rank alternatives instead combing their strengths together to get one integrated system. Forth, all input assumptions in this paper are crisp deterministic assumptions, so the outcome may become inaccurate in scenarios involving high levels of uncertainty associated with the key criteria. Fifth, criteria in this system are too rough, people need to do a lot of prep work to determine these criteria.

2.3 Discussion and summary

As reviewed in section 2.2, nowadays, the most commonly used method to select well completion method is based on experience and knowledgeable experts, which is not equipped with systematic analysis and is not accurate enough. Even though some researchers have tried to apply MODM on it, there are still a lot of improvement needed. So far, some researches have only used either subjective or objective MODM on selection, but as discussed before, they all have their own disadvantages. In addition, although some researchers have applied subjective and objective method on selecting procedures, they just used them separately and did not combine them together. Furthermore, there is no fuzzy based MODM has been used on well completion method selection, which can handle uncertainty within the system. Therefore, there is an imperative need, and this thesis is dedicated to develop an improved well completion method optimum selection system that can combine both subjective and objective MODM in one system and with fuzzy theory applied in it.

As discussed in section 2.1, AHP is a subjective method and is more suitable for this system than other methods because it is more flexible and can capture both subjective and objective evaluation measures. The most important part is personal perspectives can be combined with scientific process in AHP method. So the proposed method has adopted AHP as the basis theory. However, AHP method also has some problems, like scale problem and consistency problem. As a significant research contribution, most of them will be addressed in new system.

Chapter 3 Fundamentals of related studies

This chapter presents the basic knowledge of well completion methods, they will be used as alternatives in the selection system, their applicable conditions, advantages and disadvantages are all presented in Section 3.1. The suggested software system is based on a proposed concept of well completion method feature, so the basic principles of advanced feature theory is also described in Section 3.2.

3.1 Well completion method

Well completion is an oil drilling process technology to connect bottom hole with oil reservoir after rigs drilling to design depth. It is the last but important process of drilling, and the beginning of oil production. Well completion quality is closely linked to oil production, waterflooding and the whole exploration of oil and gas field. Whether to have a good selection of well completion methods or not can directly influence wells' production capacity and economic life, and further it can determine whether the whole oil field can get the reasonable exploration or not.

Different well completion methods generate different drainage area, crack percent, cost, producing degree of reserves and recovery efficiency. The appropriate selection of well completion can reduce formation damage, increase per-well production, lengthen the productive life of wells and improve economic returns. As described above, it is important to develop a systematic and applicable system to optimize the selection of well completion methods.

Well completion system has developed in petroleum industry for a long time, so there are some classic methods in this field. In addition, there are also some new well completion methods or improvements of these basic methods. In oil industry, wells can be basically divided into two types, vertical wells and horizontal wells. The well completion methods applied on these two kinds of wells are different because the different, e.g. adaptability, working conditions, technologies, even though some methods' name are the same. The next sections give an overview of well completion methods, both basic and some useful new methods will be presented. This review is mainly focus on the onshore condition, well completion methods for both vertical well and horizontal well will be described respectively and applicable conditions, advantages and disadvantages of these methods will be analyzed.

3.1.1 Vertical well completion methods

a. Open hole completion

Open hole completion means there is no casing or liner set across the targeted oil/gas formation, which means the production casing is set on top of the reservoir, but the reservoir formation is left without cemented casing. This method allows the produced fluids to flow directly into the wellbore. Open hole completion can be divided into initial open hole completion (Figure Appendix.1a), compound open hole completion (Figure Appendix.1b) and final open hole completion (Figure Appendix.1c). Initial open hole completion is drilling to the top of oil layer first and then putting production casing down and cementing. After mud get to the predetermined height, using a smaller diameter drill to drill to the targeted oil layer. Final open hole completion is drilling to the targeted oil layer directly without changing drill, then putting casing down to the top of the oil layer and cementing. Sometimes, the oil layer is thick enough for open hole completion, but there is a gas cap or a water layer nearby, it is a good choice to use intermediate casing to get across to oil gas interface under this situation, which can isolate upside of oil layer. Then using the open hole method for targeted layer and can perforate oil-bearing interval if it is necessary. This method is called compound open hole completion. Applicable conditions of open hole methods are:

- The lithology is consolidated and hard enough to ensure wall of well is stable and will not collapse during production.
- Strata with good porosity and permeability or good nature fractures.
- No gas cap or bottom water; no water-bearing or instable interlayer
- The targeted reservoir is a thick enough single layer or multi-layer with consistent pressure and lithology
- Do not intend to isolate different layers or further processing the targeted reservoir

Advantages of open hold completion for vertical wells:

- Suppress interference from upper formation, which can open the reservoir with minimized contamination (initial open hole completion)
- Full exposure of reservoir zone, which can improve wellbore performance due to the large inflow area
- Shorten reservoir ‘s contacting time with drilling fluid to minimize formation damage
- Minimize wellbore skin
- Minimize flow path restriction due to cementing and perforating [81]
- Can bring rig up to the casing in time when meet complex situations during opening the reservoir to avoid complicating accidents

Disadvantages of open hole completion for vertical wells:

- Unable to deal with heterogeneous or weakly consolidated reservoir
- Unable to overcome the adverse effects brought by wall collapsing and sand producing
- Difficult to do reservoir management
- Difficult to apply selective treatments or remedial work within the reservoir section without any casing or liner installed
- Inability to produce at different zones [81]
- Final open hole completion cannot totally avoid adverse effects brought by drilling fluid and mud

b. Cased hole completion

Perforated completion is the most commonly used completion technique today, which includes perforated casing completion (Figure Appendix.2a) and perforated tailpipe completion (Figure Appendix.2b).

Perforated casing completion is drilling across oil layer to designed depth, then putting production casing down to the bottom of oil layer and cementing. The last step is perforating to punch a hole in well’s casing and cement layer to connect the reservoir. Perforated Tailpipe completion is drilling to the top of the oil layer first then putting down the casing and cementing. After that, using a smaller drill to drill across oil layer to the designed depth and then put tailpipe down and hang it on the casing. Doing the cementing and perforating at last. Applicable conditions of cased hole methods are:

- Reservoirs with gas cap, bottom water, aquifer, unconsolidated interlayers or complex geological situations, which need to isolate and separate different layers
- Different pressure or lithology in different layers, which need stratification testing and producing oil and injecting water by layers
- Low permeability reservoirs that need to be applied hydraulic fracturing operation in large scale
- Reservoirs in complex structure, like reservoir with long oil-bearing strata or thick interface

Advantages of perforated completion for vertical wells [82]:

- The most economical method except open hole completion
- Better zonal isolation
- Facilitation of selective perforation and stimulation
- Effective way to complete multiple zones in one well
- Manage reservoir in a better way
- Ability to avoid any undesirable productions such as water, gas, or sand
- Ability to apply tubingless completion and multi string completion
- Ability to work over and recomplete the well
- Better well integrity
- Upper stratum has already been cemented in perforated tailpipe completion before drilling to the oil layer, so suited drilling fluid and balanced or underbalanced drilling method can be used to oil layer to protect reservoir and reduce dosage of mud and casing

Disadvantages of perforated completion for vertical wells [82]:

- Damage oil or gas reservoir in a bad way due to drilling fluid and mud
- Less connective area between reservoir and bottom hole
- High inflow resistance
- A possibility of blowout after perforating if did not get correct stratum pressure
- Not very efficient for highly-deviated and horizonal well and can be restricted with high density mud

c. Slotted liner completion

Slotted liner completion (Figure Appendix.3) is drilling to the top of oil layer, putting down the casing and cementing first, then using a smaller drill to get across that casing and oil layer to the designed depth. After that, putting the preselected slotted liner down to the oil layer and hanging it on the hanger attached to the production tubing. This method is one of the most commonly used well completion methods, which can take advantages of open hole completion and can also control sand in a certain degree. This method has simple technical process and can be operated easily, so it is generally used in some medium to coarse sand reservoir, which do not have serious sand production.

Slotted liners are made from tubulars by saw-cutting slot configurations, the minimum slot width that can be achieved is about 0.012 in. Slots that cut less than 0.020 in. in width involve high costs because of excessive machine downtime to replace broken saw blades that overheat, warp, and break [83]. There are two kinds of commonly used slot, straight slot and keystone shaped slot. The keystone shaped slot is less prone to plugging due to its inverted “V” cross-sectional area [83]. This is because the outside diameter is larger than the inside diameters, which can make sands keep passing through rather than blocking up slots.

Applicable conditions of slotted liner completion are:

- No gas cap or bottom water; no water-bearing or instable interlayer
- Thick single layer reservoir or multi-layer reservoir with consistent pressure and lithology
- No zonal isolation or selective stimulation needed
- Medium to coarse sand reservoir with loose lithology

Advantages of slotted liner completion for vertical wells:

- Damaged slotted liners can be repaired or replaced
- Oil layer do not get damage due to cementing mud
- Can adopt suitable drilling fluid and drilling technology to drill the oil layer, which can protect the reservoir
- Prevent stratum collapsing
- Simple technology and easy to operate

- Sand control

Disadvantages of slotted liner completion for vertical wells [83]:

- Limited flow area
- Minimum available slot size
- Cannot control serious sand production
- Can experience high pressure drops during production

d. gravel pack completion

Gravel pack completion is usually adopted for loose cementing strata, which can produce sand seriously. This method is packing sized gravels between screened liner and wall of well to prevent sanding and protect reservoir. The way to pack includes direct packing and pre-packing.

Direct packing is putting wire wrapped liner or slotted liner down to the oil layer and using filling fluid to pump those pre-selected gravel to the annular space between liner and well's borehole (or casing), which can form a gravel packing zone to prevent sands flow into the well.

Pre-packing is using a special wire wrapped liner, which owns inner and outer layers, so gravels can be put into the annular space between these two layers and prevent sanding. However, this method can cause low productivity and the useful life of preventing sanding is shorter compared to direct packing method. This is because pre-packing method can only prevent sand flowing into intermediate casing, but it cannot make sure there is no sand flowing into the wellbore.
Both open-hole and cased hole completion can be packed with gravels to meet the demand under different situations.

Open-hole gravel pack (Figure Appendix.4a) is useful when sanding control is needed and the geological conditions are good enough to apply open hole completion. The process is drilling to the place three meters above oil reservoir, then putting intermediate casing and cementing. The next step is using a smaller drill to drill across cement plug to the designed depth. Then using the expansion drill to expand hole diameter to 1.5-2 times larger than intermediate casing's outer diameter to make sure there is enough annular space for gravel.

The process of cased hole gravel pack (Figure Appendix.4b) is drilling to the designed depth and putting oil-string case down to the bottom of oil layer. Then, cementing and perforating the reservoir. This technology requires large aperture and high dense hole perforation, which can enlarge circulation area and sometimes can wash out the sands outside of casing to avoid increased flow resistance due to combination of gravel and formation sand.

Applicable conditions of open-hole gravel pack completion are:

- No gas cap or bottom water; no water-bearing or instable interlayer
- Thick single layer reservoir or multi-layer reservoir with consistent pressure and lithology
- No zonal isolation or selective stimulation needed
- Fine, medium or coarse sand reservoir with loose lithology and serious sand production

Applicable conditions of cased hole gravel pack completion are:

- Reservoirs with gas cap, bottom water, aquifer, unconsolidated interlayers or complex geological situations, which need to isolate and separate different layers
- Different pressure or lithology in different layers, which need stratification testing or selective stimulation needed
- Fine, medium or coarse sand reservoir with loose lithology and serious sand production

Advantages of grave pack completion for vertical wells [1]:

- Useful for controlling sand in heterogeneous formations
- Productivity impairment can be minimized by proper design
- Long operating life
- Support strata to prevent collapsing
- High successful rate

Disadvantages of grave pack completion for vertical wells [1]:

- Complex operation to install equipment and place gravel in place
- Complicated post process and high cost

3.1.2 Horizontal well completion methods

a. Horizontal open hole completion

The process for open hole completion is drilling and putting intermediate casing down to expected depth and cementing. Then using a smaller drill drilling horizontal part to designed length. (Figure Appendix.5)

Advantages of open hold completion for horizontal wells:

- Lowest cost
- No damage from mud
- Expandable packer can be used to control production and isolate layers to improve production
- Variable area flowmeters can be used to do the production examination [81]

Disadvantages of open hole completion for horizontal wells:

- Borehole may collapse in loose lithology reservoir
- Hard to avoid connections between different layers
- Cannot apply selective stimulation

b. Horizontal slotted liner completion

Slotted linear completion is hanging the liner on intermediate casing and sealing the annular space by using packer. Liner centralizer needs to be used to make sure liner stay in the center in horizontal borehole. (Figure Appendix.6)

Advantages of slotted linear completion for horizontal wells:

- Relatively low cost
- No damage from mud
- Can prevent borehole collapsing
- Horizontal part can be divided into several parts to apply small-scale stimulations

Disadvantages of slotted linear completion for horizontal wells:

- Cannot avoid connections between different layers
- Cannot apply large-scale selective stimulation
- Cannot control production
- Cannot get production testing data

c. External casing packer completion

ECP can be used in well completion method to isolate different stratum, so that production control and other operations can be applied in different layers. There are three kinds of ECP completion method, slotted liner with ECP (Figure 3.7a), ECP with sliding sleeve (Figure Appendix.7b), Cased hole with ECP (Figure Appendix.7c).

Advantages of slotted liner with ECP completion for horizontal wells:

- Lower cost than cased hole method
- No damage from mud
- Can avoid connections between different layers in a certain degree due to ECP
- Production control and production testing and selective stimulation can be applied

Disadvantages of slotted liner with ECP completion for horizontal wells:

- The effectiveness of ECP to isolate strata depends on the shape of wellbore, the pressure and temperature in strata etc., it is hard to insure the success of this method

d. Cased hole completion

Cased hole completion (Figure Appendix.8) for horizontal well is putting the casing into vertical part and cementing. Then using the tail pipe in horizontal part and the last step is perforating in horizontal part after cementing. The best overlapping part of casing and tail pipe is around 100 meters.

Advantages of cased hole completion for horizontal wells:

- The most effective method to isolate layers and avoid connections between different layers
- Production control and production testing and selective stimulation can be applied effectively

Disadvantages of cased hole completion for horizontal wells:

- Relatively high cost
- Reservoir can be damaged due to mud
- It is hard to ensure the quality of cementing
- High perforating operation skill needed

e. Gravel pack completion

There are two kinds of gravel pack completion: open-hole gravel pack and cased hole gravel pack. The technology for both two methods are complex and hard to process. The liner used in open hole completion with pre-packed wire-wrapped liner in horizontal well (Figure Appendix.9a) has the same properties as in vertical well, but centralizer needs to be used here to keep liner in the middle. The cased hole completion with pre-packed wire-wrapped liner (Figure Appendix.9b) is finishing the cased hole first and then putting the pre-packed wire-wrapped liner down.

Advantages of open hole completion with pre-packed wire-wrapped liner for horizontal wells:

- No damage from mud
- Can prevent sanding in loose reservoir and wellbore collapsing

Disadvantages of open hole completion with pre-packed wire-wrapped liner for horizontal wells:

- Cannot avoid connections between different layers
- Cannot apply selective stimulation
- Cannot control production
- Cannot get production testing data

Advantages of cased hole completion with pre-packed wire-wrapped liner for horizontal wells:

- Can prevent sanding in loose reservoir and wellbore collapsing
- Especially useful in thermally recovered viscous crude oil reservoirs
- Can select perforated zone

Disadvantages of cased hole completion with pre-packed wire-wrapped liner for horizontal wells:

- Reservoir can be damaged due to mud
- The pre-packed wire-wrapped liner needs to be gotten out before applying selective stimulation

f. Expandable tubular well completion

The concept of expandable tubular uses the cold drawing process to shape steel tubulars to the required size[84] and putting it down to the bottom hole and then using mechanical or hydraulic pressure to pull or press the string to generate permanent plastic deformation, which can increase the inner diameter of the string. The most common method consists of pumping and seating a dart to create the pressure chamber needed at the launcher, this allows hydraulic force to be generated to move the expansion cone upwards during the expansion process [84]. Expandable tubular basically includes expandable slotted liner and expandable sand control screen pipe and they usually consist of expandable slotted steel tube, overlapped metal screen and expandable slotted shroud. Expandable liner has obvious advantages compared with conventional liner (Figure Appendix.10), for example, it decreases gap between liner and wall of well, which can increase open area and decrease flow resistance.

Advantages of expandable tubular well completion for horizontal wells [85]:

- Larger inner diameter, which can decrease pressure drop under high liquid flow rate and decrease oil flowing resistance by increasing open area
- Support wall of wells and decrease the possibility of collapsing
- Increase the efficiency and prolong the useful life of sand control liner by decreasing plugging and erosion destruction
- Do not need to pack gravel under appropriate strata conditions
- Simple construction process and few ground equipment, which can be easily applied in horizontal, highly-deviated and multilayer wells
- Decrease the damage caused by cementing and perforating

Disadvantages of expandable tubular well completion for horizontal wells:

- Cannot insure “zero gap” between liner and well wall in irregular borehole
- It is hard to fix if the liner cannot expand successfully
- Hard to deal with tool sticking due to low tensile strength of expandable liner

3.2 Feature modeling in Engineering Informatics

3.2.1 Engineering informatics

Engineering informatics is an interdisciplinary scientific area, which combines information technology (IT) with engineering concepts. It is usually applied to assist managing engineering activities to improve products’ quality or better handle complicated engineering processes.

Engineering informatics has been applied in many engineering areas, like product design and development, concurrent and collaborative engineering etc. [86] and an appropriate engineering informatics framework and detailed models are critical for engineering managements; they can be really helpful for both product and process engineering.

3.2.2 Definition of feature

Feature was introduced in the late 70s as modeling elements in CAx systems [87], Feature modeling technique is widely applied on engineering field, and this results in people under different application background and in different design phases can have different understanding about feature. In addition, with further study on feature technique, more morphologies of feature have been developed, and more information has been included in it. Therefore, we can say feature is possessed of polymorphism and expansibility. Because of these two characteristics, researchers have defined feature from different perspectives:

- Shah et al. (1991) [88]: Feature is a carrier of information, which can help communications between engineering tasks, like design, manufacture etc.
- Shah and Mäntylä (1995) [89]: Feature is an information cluster, which is used for gather engineering data. In addition, it is also a physical constituent of a part.

- Brunetti et al. (2003) [90]: Feature is not restricted to physical elements and can be used to represent both geometric and non-geometric information about products.
- Di Stefano et al. (2004) [91]: The overall aim of feature-based representation is to convert low level geometrical information into high level description in terms of form, functional, manufacturing or assembly features.
- Y.-S Ma et al. (2013) [92]: Feature is a representation of an engineering pattern that formalizes the associations between relevant data, using object-oriented software modelling terminology.

According to Ma's recent works [93] [94] [92] , any part of a process or a product whose change can have engineering meaning on the system and make it behave in a different way can be called a feature.

Feature based modeling is building frameworks and models by using feature templates, it includes recognizable entities that have specific representations designed to support a specific application purpose as a working system [86]. The number and type of features that are included to form a complete model depends on the function that is intended to be supported, which makes feature models inherently modular and scalable.

3.3 Discussion and summary

This chapter introduces the fundamentals of various well completion methods for both vertical and horizontal wells, and their advantages and disadvantages have been analyzed to guide the final selection. Furthermore, feature modeling has been introduced, and different definitions of feature have also been discussed.

Chapter 4: Well completion method selection system structure and evaluation system

The above proposed system can be divided into three modules, input information and representation module, evaluation module, and optimal selection module, which is shown in Figure 4.1, This chapter introduces the evaluation module in details.

The selection of well completion method is an integrated decision-making process with multi-objectives The valuation module is a major component of the whole optimum selection system. The evaluation module is a data source. A comprehensive evaluation module can make the final decision more reasonable. The evaluation module proposed by this research works includes influence factors from different perspectives, and their interrelationship has also been figured out.

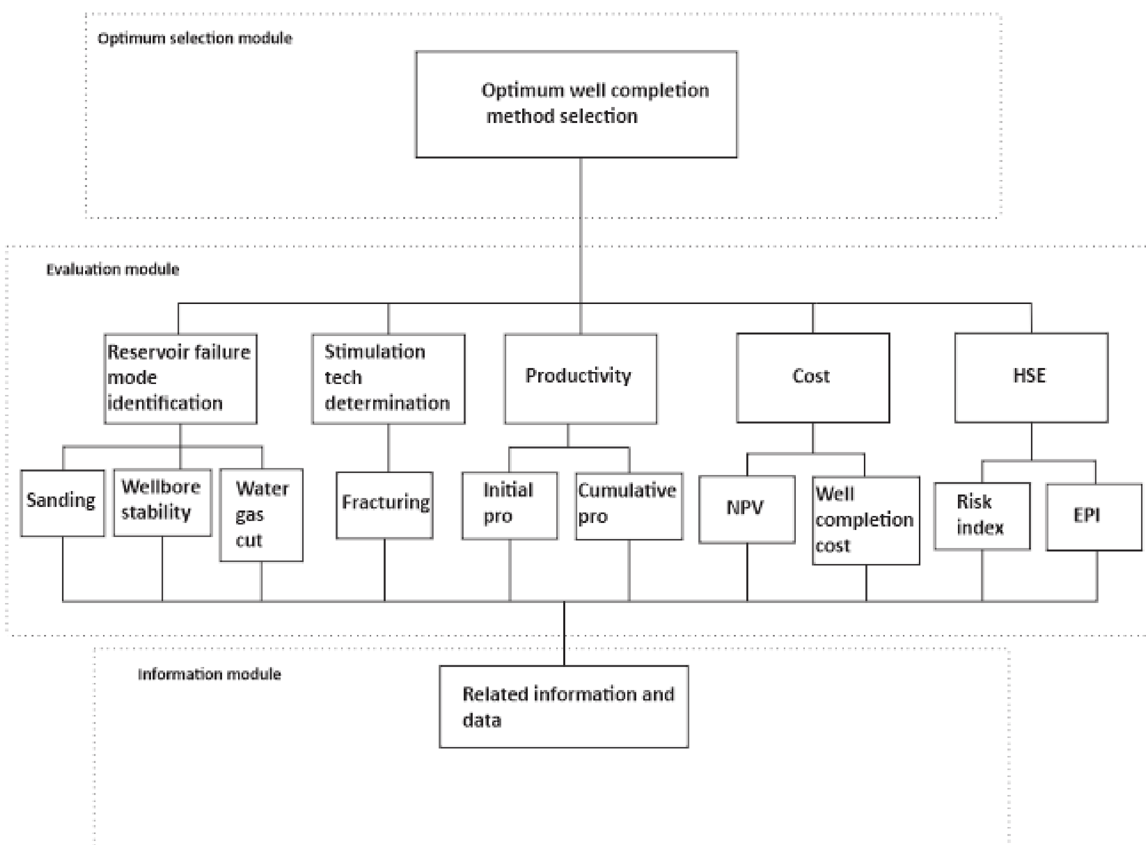


Figure 4. 1 Proposed well completion method selection system diagram

4.1 Reservoir failure mode identification

Different reservoir has different geological conditions that could lead to different failure modes, like sanding, wellbore collapsing etc. Because these failures can cause the whole well scrap directly, appropriate well completion methods need to be applied to protect wellbores. However, extra protective measures usually mean extra cost and time, so it is important to identify the possible failure modes for each well to prevent wasting money and time.

Before introducing evaluation system, there are two points needed to be clarified first. One is weighting point is used in this chapter to represent quantified indexes. A weight point is a generic measure of probability of event state to occur with a specific variable range of measured values, from 0 to 1, “0” means the 100% probability of low limit measure to occur while “1” indicates the 100% probability of high limit event. For example, when weighting point equals 0.5, that means there is 50% chance of the variable that falls in the high limit side of the range, while also 50% chance in the low limit side.

The second is the weighting point is using 0.1-0.9 scaling method, some researches have done and lots of papers used this method [95] [96] [97] [98] to demonstrate that it can better reflect people’s subjective judgement and it is easily operated because it matches with the qualitative way of human being’s thoughts and expression.

Three crucial failure modes are considered in the evaluation module of the proposed system and will be analysed respectively in following subsections.

4.1.1 Sand production

Sand production is a big concern for oil companies, because it can lead to significant loss in well production, erosion in downhole and damage on facility. Serious continuous sanding can cause shut-in of the well [99]. However, on the other hand, precautionary but unnecessary sand prevention will lead to unpredictable loss on productivity [100]. Therefore, it is necessary to include sanding prediction in this well completion selection system.

There are many factors can influence sanding and lots of analytical methods have been proposed to predict sanding. Some of these methods are based on laboratory tests, others are based on experiences, and they usually consider sanding problem from different aspects. As shown in Figure 4.1 this system combines both quantitative and qualitative methodologies to consider sanding problem from multi-angle and to improve accuracy of sanding prediction.

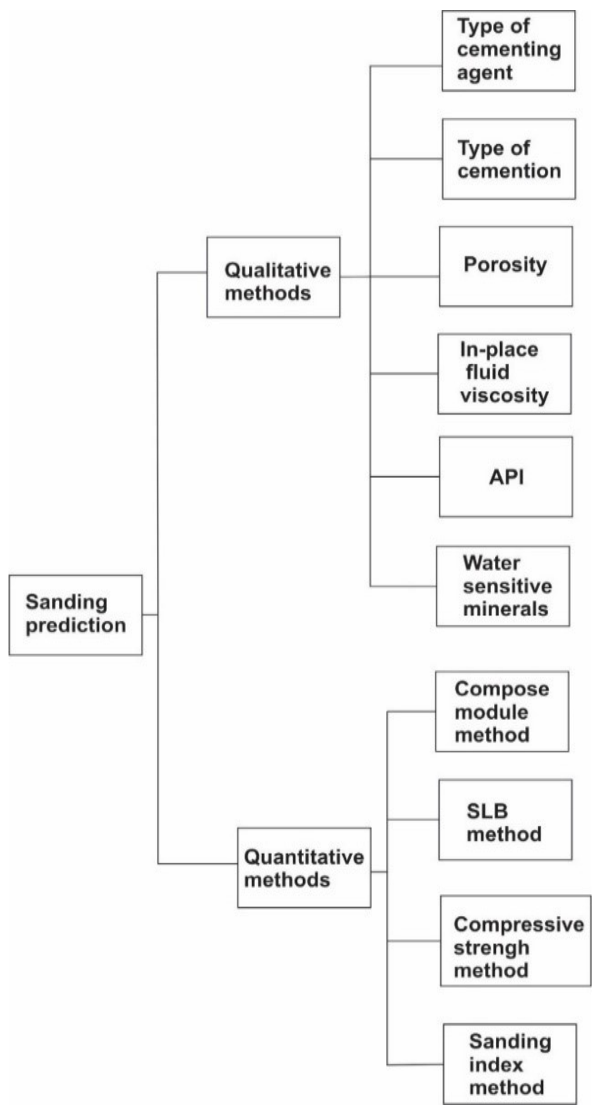


Figure 4. 2 Judgement criteria of sanding

a. Type of cementing agent

Cements are crystalline materials between clasts to bind them together, and the process to form cements is called cementation. Cements are precipitated ions carried in groundwater, they are integral part of rocks. In other word, cement agents are connections between sedimentary grains, and they can influence the strength of rocks. There are many kinds of cementing agent, the most common types in oil reservoirs include argillaceous, siliceous, calcareous, ferruginous cements [101]. Different kinds of cements can lead to different strength of rocks and different possibility of sanding.

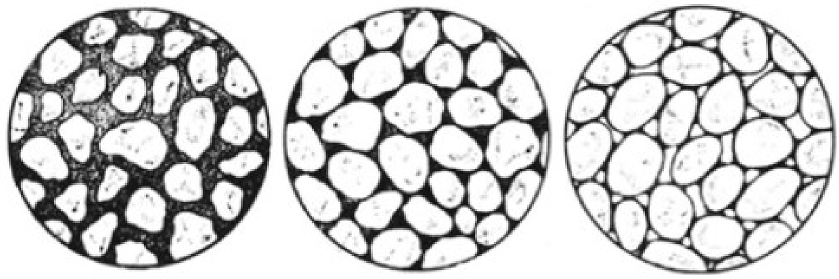
Argillaceous cement contains substantial amounts of clay minerals, like illite, kaolinite, montmorillonite-smectite, etc., and it is the weakest cementing agent. Siliceous cement mainly includes opal, chalcedony and crystalline quartz, the strength of rocks cemented by siliceous minerals is stronger than argillaceous based but weaker than calcareous based rocks. Limonite and hematite are the most common minerals in ferruginous cement, and the strength of ferruginous based rocks are almost the same as siliceous based. Because type of cements is a qualitative factor, so quantification needs to be applied. The weighting point of different type of cementing agents is shown in Table 4.1.

Table 4. 1 Quantitative value of cementing agents

Type of cementing agent	Argillaceous cement	Siliceous cement	Calcareous cement	Ferruginous cement
Weighting point for probability of sanding	0.9	0.3	0.7	0.3

b. Type of cementation

The contact and distribution pattern of cementing agents and grains is called cementation type [101]. The cementation type of a rock primarily depends on the proportion of grains and matrix, and interrelation between them. There are mainly three cementation types exist in rocks: basal, porous, and contact cementation.



(a) Basal cementation (b) Porous cementation (c) Contact cementation

Figure 4. 3 Three types of cementation (Zhu, 2008) [101]

- Basal cementation: There is a big distance between particles. As shown in Figure 4.2 a, particles usually do not contact with each other and “float” in cementation. Cements in basal cementation are formed in the period of sedimentation, so the basal cementation is also called progenetic cementation [101]. Because the support from large amount of matrix, the connection between grains is very strong and is usually hard to break.
- Porous cementation: It is a grain-supporting structure with most of grains are of point contact. Porous cementation generally represents sedimentation of stable fluids or wave washing. As shown in Figure 4.3 b, it has less cements than basal cementation, so the strength of rocks with porous cementation is weaker.
- Contact cementation: This kind of cementation also belongs to grain-supporting type, and cements only appear in places where grains contact with each other. Contact cementation exists in stones formed under relatively specific conditions. Cements are very rare in contact cementation, so the strength of it is the weakest among these three types of cementation. Contact cementation is shown in Figure 4.3 c.

The weighting point of different type of cementing agents is shown in Table 4.2.

Table 4. 2 Quantitative value of cementation

Type of cementation	Basal cementation	Porous cementation	Contact cementation
Weighting point for probability of sanding	0.3	0.7	0.9

c. Porosity

Porosity is the ratio of rock's void space to its total volume. Larger the porosity, larger the space to store oil and gas. Not all pores have practical values, only the pores that can connect with each other can be used to extract oil out. Therefore, porosity is a very important parameter for reservoir assessment, the stratum with high porosity is generally defined as high quality reservoir. However, high porosity also means less support within stratum, and this often causes instability and sanding while producing oil, so porosity should also be included in the evaluation module. The weighting point of porosity is shown in Table 4.3

Table 4. 3 Quantitative value of porosity

Porosity	>30%	20%-30%	<20%
Weighting point for probability of sanding	0.9	0.7	0.3

d. In-place fluid viscosity

Viscosity provides a measure of a fluid's internal resistance to flow, higher the viscosity, harder the fluid to flow. For a reservoir, high in-place fluid viscosity means high drag force while fluids flowing toward wellbore, so the possibility of sanding is high. That is why reservoirs with heavy oil always need to control sanding. The weighting point of in-place fluid viscosity is shown in Table 4.4.

Table 4. 4 Quantitative value of fluid viscosity

In-place fluid viscosity (MPa·s)	<10	10-50	>50
Crude oil classification	Light crude oil	Medium crude oil	Heavy crude oil
Weighting point for probability of sanding	0.3	0.7	0.9

e. API gravity

API stands for the American Petroleum Institute, which is the major United States trade association for the oil and gas industry. API gravity is a measure to determine the weight of oil in comparison to water. The quality of oil can be judged by API gravity, light oil's API is higher than 31.1, medium oil's API is lower than 22.3, and the oil whose API is lower than 10 is called heavy oil or asphalt oil, for example, the oil produced from Alberta's oil sand is heavy oil, its API is usually lower than 8. Therefore, lower API gravity represents higher possibility of sanding. The weighting point of API gravity is shown in Table 4.5.

Table 4. 5 Quantitative value of API gravity

API	>31.1°	22.3°-31.1°	<22.3°
Crude oil classification	Light crude oil	Medium crude oil	Heavy crude oil
Weighting point for probability of sanding	0.3	0.7	0.9

f. Water-sensitive minerals

There are some water-sensitive minerals exist in strata, like montmorillonite, illite, smectite and chlorite. They are very sensitive to free water, so they will swell, disperse and move when meeting the drilling slurry, this is called water sensitive effect. Water-sensitive minerals can decrease the strength of rocks and aggravate sanding because of their expansion and movement.

The weighting point of water-sensitive mineral is shown in Table 4.6.

Table 4. 6 Quantitative value of water-sensitive mineral

Water-sensitive minerals	Include a lot of montmorillonite, illite, smectite or chlorite	Include some montmorillonite, illite, smectite or chlorite	Do not include montmorillonite, illite, smectite or chlorite
Weighting point for probability of sanding	0.9	0.7	0

g. Compose module method

The strength of strata has close relationship with rocks' dynamic modulus of elasticity, such as shear elasticity and bulk modulus. Shear elasticity is the ratio of shear loading and transverse strain; bulk modulus is the reciprocal of rock compressibility and it is determined by grains and fluids' compressibility. Compose module method utilizes these properties and gets an experience-based equation.

$$E_c = \frac{9.94*10^8*\rho}{\triangle t_c^2} \text{ [102]} \tag{4.1}$$

$\rho - Density\ of\ rock\ (g/cm^3); \triangle\, t_c\ - Compressional\ wave\ slowness\ (\mu s/m)$

The Lower E_c, the higher possibility of sanding, and the judgement criteria are shown in Table 4.7.

Table 4. 7 Judgement criteria and weighting point of compose module method

E_c	$\geq 2.0 * 10^4 MPa$	$1.5 * 10^4 - 2.0 * 10^4 MPa$	$\leq 1.5 * 10^4 MPa$
Weighting point for probability of sanding	0	0.7	1

h. SLB method ($\frac{G}{C_h}$)

SLB method is proposed by Schlumberger company, this method also predicts sanding using rocks' dynamic modulus of elasticity. Schlumberger company have tried to apply this method on Gulf of Mexico, State of California, Trinidad, Canada and India etc. and all got accurate results.

$$\frac{G}{C_h} = \frac{(1-2\mu)(1+\mu)\rho^2}{6(1-\mu)(\triangle t_c)^4} * (9.94 * 10^8)^2 \text{ [102]} \tag{4.2}$$

$G -$ Shear modulus of rock (MPa)

$C_h -$ Rock's coefficient of volume compressibility (1/MPa)

$\mu -$ Poisson's ratio of rock

$\rho -$ Density of rock (g/cm^3)

$\Delta t_c -$ Compressional wave slowness (μ s/m)

The judgement criteria are shown in Table 4.8.

Table 4. 8 Judgement criteria and weighting point of SLB method

$\frac{G}{C_h}$	$>3.8 * 10^7 MPa^2$	$3.3 * 10^7 - 3.8 * 10^7 MPa^2$	$< 3.3 * 10^7 MPa^2$
Weighting point for probability of sanding	0	0.7	1

i. Sanding index method

This method uses logging data, like transverse interval transit time, density of rock etc. to calculate mechanical parameters of rock and then to predict sanding condition. However, this method is concluded based on experience, so different oil field may have different sanding critical value. This thesis adopts the most common critical value and is shown in Table 4.9.

$$B = K + \frac{4}{3}G \; [103] \tag{4.3}$$

$$K = \frac{E}{3(1-2\mu)} \; [103] \tag{4.4}$$

$$G = \frac{E}{2*(1+\mu)} \; [103] \tag{4.5}$$

B − Sanding index (MPa)

K − Bulk modulus (MPa)

G − Shear modulus (MPa)

E −Young's modulus (MPa)

μ − Poisson's ratio of rock

Table 4. 9 Judgement criteria and weighting point of sanding index method

B	$\geq 2.0 * 10^4 MPa$	$1.4 * 10^4 - 2.0 * 10^4 MPa$	$\leq 1.4 * 10^4 MPa$
Weighting point for probability of sanding	0	0.7	1

j. Compressive strength method

This is a method considers both the strength of rock and wellhole, it not only includes geological factors, but also includes factors of production. Because the reservoir pressure will become lower and lower after producing oil, which means rocks will handle more pressure, and rocks will break when this pressure is bigger than rocks' shear force resistance.

The equation of this method is different for vertical wells and horizontal wells.

For vertical wells:

$$\sigma_t = 2[\frac{\mu}{1-\mu}(10^{-6}\rho g H - \rho_s) + (p_s - p_{wf})] \; [102] \tag{4.6}$$

C − Compressive strength of rock (MPa)

σ_t − Maximum shear force of rock (MPa)

p_{wf} − Flowing bottom hole pressure, FBHP (MPa)

ρ − Average density of overlying rock (kg/m^3)

g − Gravity of acceleration (m/s^2)

μ − Poisson's ratio of rock

p_s − Reservoir pressure (MPa)

H − Depth of reservoir (m)

For horizontal wells:

$$\sigma_t = \frac{3-4*\mu}{1-\mu}(10^{-6}\rho g H - \rho_s) + 2(p_s - p_{wf}) \; [102] \tag{4.7}$$

C − Compressive strength of rock (MPa)

σ_t − Maximum shear force of rock (MPa)

p_{wf} − Flowing bottom hole pressure, FBHP (MPa)

ρ − Average density of overlying rock (kg/m^3)

g − Gravity of acceleration (m/s^2)

μ − Poisson's ratio of rock

p_s − Reservoir pressure (MPa)

H − Depth of reservoir (m)

As we can see from equation 4.8 and 4.9, under the same buried depth, horizontal wells are easier to produce sand than vertical wells. This is because the poisson's ratio of rock is usually between 0.15 to 0.4, so (3-4μ）>2μ, which means the wall of horizontal well needs to handle bigger tangential stress than vertical well. Judgement criteria are shown in Table 4.10.

Table 4. 10 Judgement criteria and weighting point of compressive strength method

σ_t	$C \geq \sigma_t$	$C < \sigma_t$
Weighting point for probability of sanding	0	1

4.1.2 Wellbore stability

In drilling operations, wellbore stability is a world-wide problem, the costs to deal with instability problems is tremendous, around 500 million dollars are spent every year [104]. Wellbore instability can cause lost circulation when tensile failure occurs, and can cause caving and hole closure when collapse failure occurs [105]. Therefore, it is necessary to adopt wellbore supported well completion method when needed. However, on the other hand, unnecessary wellbore supported equipment will increase not only the cost, but also the difficulty of construction. Hence, the evaluation module in this thesis includes the wellbore instability prediction to make the final selection more reasonable and accurate.

The two most commonly used rock failure criteria in wellbore stability analyses are Mohr-Coulomb criteria and the Drucker-Prager criterion. They consider the stability problem from different perspectives, so this system includes all of them, and different companies can give different weight on these criteria based on companies' own data and situation.

a. Mohr-Coulomb criterion

The Mohr-Coulomb criterion represents the linear envelope that is obtained from a plot of the shear strength of a material versus the applied normal stress. It assumes that the intermediate principal stress has zero influence on rock strength.

$$\sigma_1 \leq 2S_o \tan\left(\frac{\pi+2\Phi}{4}\right) + \sigma_3 tan^2(\frac{\pi+2\Phi}{4}) \text{ [105]} \quad (4.8)$$

Where σ_1 and σ_3 are the maximum and minimum effective principal stresses, S_O is the rock cohesive strength, and Φ is friction angle. Collapse failure will not occur when Eq. 4.10 is satisfied.

Table 4. 11 Judgement criteria and weighting point of Mohr-Coulomb criterion

Whether satisfied Mohr-Coulomb criterion	Satisfied	Not satisfied
Weighting point for probability of wellbore collapse occurrence	0	1

b. Drucker-Prager criterion

The Drucker-Prager criterion is a three-dimensional pressure-dependent model to estimate the stress state at which the rock reaches its ultimate strength [106]. This failure criterion gives just as much weight to the intermediate principal stress as it does to the major and minor principal stresses.

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \leq [A + B(\sigma_1 + \sigma_2 + \sigma_3)]^2 [105] \tag{4.9}$$

Where A and B are a combination of rock properties and pore pressure, and are given by

$$\mathrm{A} = \frac{3(S_o - \alpha_0 P tan\Phi)}{\sqrt{9 + 12tan^2\Phi}} \tag{4.10}$$

$$\mathrm{B} = \frac{tan\Phi}{\sqrt{9 + 12tan^2\Phi}} \tag{4.11}$$

α_0 is Biot poroelastic constant and P is pore pressure. Collapse failure will not occur when Eq. 4.9 is satisfied.

Table 4. 12 Judgement criteria and weighting point of Drucker-Prager criterion

Whether satisfied Drucker- Prager criterion	Satisfied	Not satisfied
Weighting point for probability of wellbore collapse occurrence	0	1

4.1.3 Water/ gas cut

Water cut is high pressure water may invade into wellbore when the well located in a reservoir with bottom water or edge water. Water cut can cause serious damage to reservoir strata. First, it can shrink the flow path of oil by making clay components expand. The second, it can break the continuity of oil flow by turning single phase flow into multiphase flow to increase the resistance of flowing. Thirdly, it can also increase flow resistance by causing water lock effect. In addition, the invasive water can generate precipitate in pores to reduce porosity and plug pores.

There are three ways of gas cutting: the first one is because drilling well can cause break of rocks, so gas exist within pores will spill out can invade into drilling fluid. The second way is the gas in gas cap can diffuse and get into reservoir strata. The third way is when bottom hole pressure smaller than formation pressure, then the stratum is under underbalance condition and then gas will invade into drilling fluid.

Water/gas cut always happens when a well is drilled in the reservoir with bottom/edge water or gas cap, so the best way is to isolate these water/gas layers. Based on that, the criteria of water/gas cut are shown in Table 4.13 and Table 4.14.

Table 4. 13 Judgement criteria and weighting point of water cut

Bottom water/Edge water	Has bottom/edge water	Does not have bottom/edge water
Weighting point for probability of water cut occurrence	1	0

Table 4. 14 Judgement criteria and weighting point of gas cut

Gas cap	Has gas cap	Does not have gas cap
Weighting point for probability of gas cut occurrence	1	0

4.2 Stimulation technology determination

Traditionally average rate of recovery is thirty-five percent for oil and seventy percent for gas, and because it is hard to find new reservoirs now, oil industry is trying to improve the recovery rate to get fifty percent recovery rate for oil and eighty percent for gas [107]. Therefore, some stimulation technologies have been proposed to improve recovery rate, the two most common and effective methods are fracturing and acidizing, and special well completion methods are needed to apply stimulation technology. However, not all reservoirs or wells are compatible with these stimulation technologies, so this section builds a model to determine the need of fracturing.

Fracturing is commonly done hydraulically. This technique is to inject pressurized liquid into wellbore to create cracks in rocks. After a period of time of producing oil, the productivity and permeability will decrease, fracturing can improve the flowing environment of oil to improve the productivity. However, fracturing involves high cost and high risk, so the selection of candidate well needs to be careful and considered from various perspectives.

There are different factors that influence the effect of fracturing, like static geological parameters and dynamic development data. In order to identify appropriate influence factors, some questions needed to be considered: does this parameter have prominent influence on fracturing effect? Whether this parameter easy to get or not? Is this parameter easy to be quantified? As shown in Figure 4.3, this thesis considers influence factors from three perspectives: productivity, oil content properties and petrophysical properties. Each parameter not only has significant influence on fracturing effect but also is convenient to get and easy to be quantified.

The rules of selecting well to apply fracturing are:

- This well needs to have enough recoverable reserves.
- This well needs to have enough producing energy.
- This well needs to have certain distance to oil-water interface.

a. Petrophysical properties

Petrophysical properties includes permeability and effective porosity. They are used to measure whether the reservoir worth fracturing or not. If this reservoir has very high permeability and porosity, then there is no need to create additional cracks to improve oil's flowability. Permeability is the ability of rock for fluids to flow through it under certain differential pressure. It is affected by rock's porosity, pores' shape, size and arrangement of grains, and is independent of fluids' properties. High permeability means fluids can get through rocks quickly, hence it is easier to extract oil and the recovery of oil is higher than low permeability reservoirs. Therefore, stratum with high permeability represents high quality reservoirs. Porosity has been introduced in previous section, it is the ratio of rock's void space to its total volume. Larger the porosity, larger the space to store oil and gas.

b. Oil content properties

Net pay thickness and recoverable reserves are used to determine whether the oil reserve is worth fracturing or not. Water saturation is the ratio of water volume to pore volume, low water saturation means high oil saturation and better effect of fracturing. Flowability coefficient is used to show the flowability of oil within reservoir, and smaller flowability coefficient leads to higher fracturing effectivity.

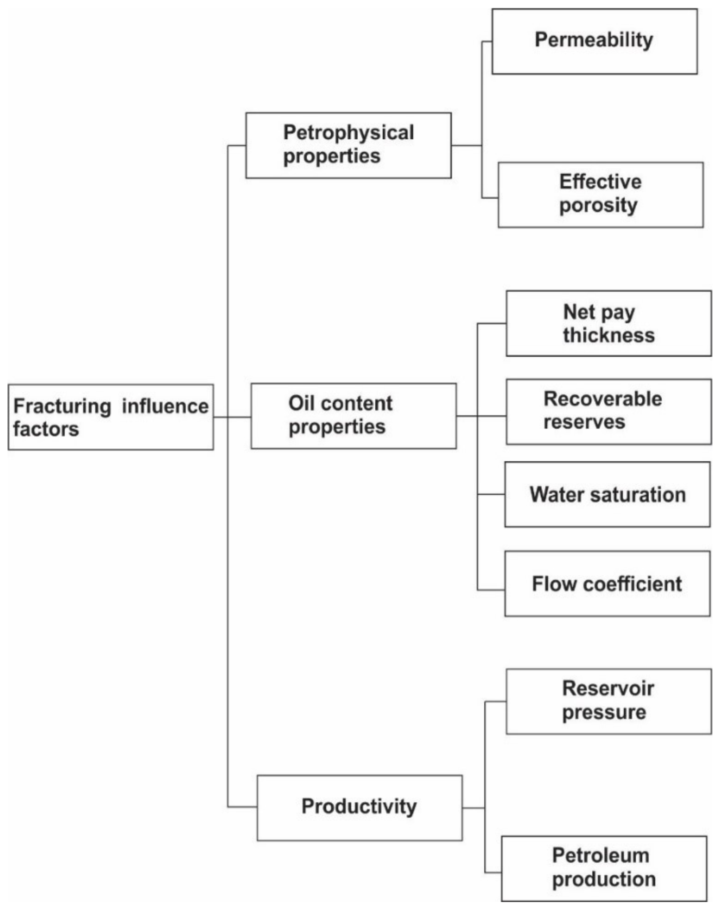


Figure 4. 4 Evaluation criteria of fracturing

c. Productivity

This section includes two factors. Reservoir pressure is an important factor, and low pressure usually leads to poor performance of fracturing, like quick production decline, short stable production phase etc. High reservoir pressure can guarantee enough fluid production ability to help fracturing. As discussed before, low petroleum production means high need of fracturing, so fracturing is usually applied when this parameter is very low.

Due to different dimensions of these influence factors, normalization needs to be applied on. Table 4.15 shows interval value of each factor, which is concluded by collecting data from general sandstone reservoirs and can be modified to fit different reservoirs.

Table 4. 15 Interval values of fracturing's influence factors

Number	Symbol	Influence factor	Interval value [A, C]
1	B_1	Permeability ($10^{-3}\mu m^2$)	[1, 500]
2	B_2	Effective porosity (%)	[2, 50]
3	B_3	Net pay thickness (m)	[2, 10]
4	B_4	Recoverable reserves ($10^8 m^3$)	[0.01, 5]
5	B_5	Water saturation (%)	[5, 60]
6	B_6	Flow coefficient ($10^{-3}\mu m^2 \cdot m/mPa \cdot s$)	[100, 1000]
7	B_7	Reservoirs pressure (MPa)	[5, 30]
8	B_8	Petroleum production (t/d)	[1, 30]

For the normalization, there are two kinds of indexes, the first is the bigger the better, which includes net pay thickness, recoverable reserves, reservoir pressure:

$$x_i = \left|\frac{B_i - A_i}{C_i - A_i}\right| \tag{4.12}$$

The second kind is the smaller the better, which includes permeability, porosity, water saturation, production and flow coefficient:

$$x_i = 1 - \left|\frac{B_i - A_i}{C_i - A_i}\right| \tag{4.13}$$

Where i is the sequence number of influence factors.

The next step is to determine whether the fracturing is needed or not. As shown in Table 4.16, this thesis divides it into four levels, D level means this well does not need fracturing to stimulate productivity, C means this well may be appropriate for fracturing, B represents the well is appropriate for fracturing, and A means the well is perfect for fracturing. These levels can also be modified based on requirements.

Table 4. 16 Fracturing needed level

Level	D	C	B	A
Interval [Y, Z]	[0, 0.25]	[0.25, 0.5]	[0.5, 0.75]	[0.75, 1]

Details of mathematical calculation will be introduced in chapter 5.

4.3 Productivity

Productivity represents production capacity of a well completion method, and it is a crucial index in this selection system. For oil industry, productivity means investment return rate, i.e. economic benefit. This thesis chooses initial production and cumulative production as specific evaluation indexes. The production calculation is based on conventional mathematical model, which includes skin factors of different well completion methods. In addition, the production calculation model is divided into two categories by well-type: horizontal well and vertical well.

4.3.1 Skin factor

Skin factor is a numerical value used to analytically model the difference from the pressure drop predicted by Darcy's law due to skin. When the reservoir production is established, the flowlines converge towards the well with a radial geometry. This defines the most fundamental flow regime in well testing: radial flow regime. Different well completion methods will cause damage in different degree and add different additional pressure drop, so different well completion method has different skin factor, and can has significant impact on oil production. There are some formulas can be used to calculate skin factor, however, complex simulation usually needed to get accurate skin factor.

4.3.2 Initial production

Initial production is the measurement of an oil well's production at the outset. Horizontal wells usually have initial production rates three to seven times of vertical wells, but their decline rates are also higher.

- For horizontal wells [108]:

$$J_{ho} = \frac{542.8hK_h/(B_0\mu)}{\ln\left[\frac{a+\sqrt{a^2-\left(\frac{L}{2}\right)^2}}{\frac{L}{2}}\right]+\frac{\beta h}{L}\ln\left[\frac{\left(\frac{\beta h}{2}\right)^2+(\beta\delta)^2}{\frac{\beta h r_w}{2}}\right]+(\frac{\beta h}{L})S} \quad (4.14)$$

β − Anisotropy coefficient of reservoir $= \sqrt{K_h/K_v}$

δ − Borehole's eccentric distance, m

(vertical distance between reservoir center and horizontal well location)

K_h − Horizontal permeability, μm^2

K_v − Vertical permeability, μm^2

B_0 − Oil formation volume factor, decimals

h − Reservoir height, m

$a = \frac{L}{2}[\frac{1}{2}+\sqrt{\frac{1}{4}+\frac{1}{\left(\frac{L}{2r_e}\right)^4}}]^{\frac{1}{2}}$ − Half the major axis of drainage ellipse, m

r_e − Drainage radius, m

L − Horizontal well length, m

μ − Fluid visosity, mPa · s

r_w − Wellbore radius, m

S_{ho} − Skin factor, dimensionless

- For vertical wells:

$$J_O = \frac{2\pi kh * 86.4}{\mu B_0(ln\frac{r_e}{r_w}-\frac{3}{4}+S)} \quad (4.15)$$

K − Horizontal permeability, μm^2

h − Reservoir height, m

B_0 − Oil formation volume factor, decimals

μ − Fluid visosity, mPa · s

r_e − *Drainage radius*, *m*

r_w − *Wellbore radius*, m

S − Skin factor, dimensionless

4.3.3 Cumulative production

Cumulative production is defined as the gross amount of oil and gas production from an oil reservoir over a time span. Ideally, cumulative production of a well is calculated annually. The equation used for cumulative production calculation is shown below [109].

$$Q = Q_i[aln\frac{e}{(1+t)^{0.182}} + be^{-0.015(1+t)}] \quad (4.16)$$

$$Q_c = \begin{cases} Q[36.06t + 5.56(1-t)\ln(1+t)], t \leq 179 \\ Q\left[1451.5 - 2033.3e^{-0.015(1+t)}\right], t > 179 \end{cases} \quad (4.17)$$

$Q_c - Cumulative\ prodution, t$

$\mathrm{t - time, Mon}$

$Q_i - Inital\ prodution, t/d$

4.4 Economic indexes

Economic indicator has significant influence on the selection of well completion methods. It is important for both oil fields and well construction companies. For oil fields, consider economic indicator can save well completion cost and get more economic benefit within a shorter period. For construction contractors, a well completion method with appropriate cost can build a good and long-term cooperation with the operator and gain more benefits. This section considers economic evaluation from two perspectives: cost and benefit, which are well completion cost and NPV.

4.4.1 Well completion cost

Well completion cost (I_w) is the measure fee included in well completion process. It contains investment and other related cost. The breakdown of well completion cost including completion rig cost (I_r), labor and supervision cost (I_s), casing and other equipment cost (I_e), transportation cost (I_t), and contingencies (I_c).

$$I_w = I_r + I_s + I_e + I_t + I_c \quad (4.18)$$

4.4.2 Net present value (NPV)

Net present value (NPV) analysis is a method of calculating the expected net monetary gain or loss from a project by discounting all expected future cash inflows and outflows to the present point in time. It is a very useful method to determine the economic feasibility of a project. In this section, every year's discounted net cash flow is calculated and add up to get NPV. A positive NPV represents the project will be a profitable one because the benefit will exceed the investment and its capital costs. On the opposite, negative NPV means this project will lose money.

$$\text{NPV} = \sum_{t=0}^{n_0}(C_g - C_h)Q_t(1+i_0)^{-t} - I \quad [110] \tag{4.19}$$

$C_g -$ Price of oil ($/t)

$C_h - Investment\ (\$ / t)$

$Q_t - Production\ in\ year\ t\ (t)$

$i_o - Discount\ rate$

n − Number of time period

I − Well completion cost

4.5 Health, safety and environment (HSE)

HSE stands for health, safety and environment. Nowadays, oil industry is putting more and more attention on workers' health and safety to avoid severe accident in this high risky industry, so HSE management system has become more important than before, and risk analysis is a crucial part within this system. In addition, in order to prevent serious damage on environment, EPI (Environmental protection index) should be considered in the well completion selection system.

4.5.1 Environmental protection index (EPI)

EPI represents environmental protection index, it mainly includes complexity of construction, time duration of operation, and influence on environment. Quantification results of this index is shown in Table 4.17, the scope of scale value is from 1 to 10 and is divided into four classes, which can transfer the qualitative data into quantitative value and make them have engineering significance. For example, 8 in EPI represents this well completion method has complex and hard construction procedures, long operating time, and have strong bad influence on the environment.

Table 4. 17 Quantitative value of EPI

Scale value	Interpretation

1-3	Simple construction, short operation time, weak impact on environment
3-5	Relatively simple construction, short operation time, relatively weak impact on environment
5-7	Relatively complex construction, relatively long operation time, relatively strong impact on environment
7-10	Complex construction, long operation time, multiple fluids get involved, strong impact on environment

4.5.2 Risk index

Risk index is also a qualitative factor and cannot be calculated directly, however, risk index is a particularly important index in oil industry, so a scientific and reasonable analysis needs to be applied on it. This thesis adopts a classic analytical tool, called fault tree analysis. Fault tree model is set up in this section to qualify risk index. A well completion method fault tree is established based on risks in well completion methods and it is shown in Figure 4.5. This fault tree reveals the relativity between top event and bottom failure event, as shown in Figure 4.5, each failure has its corresponding reasons, and these reasons assist to determine the probability of each failure. In fault tree analysis theory, cut set is a gather of bottom events that can lead to a top event, and the minimal cut set means the minimal number of bottom events can cause a top event happens. The possibility of failure can be calculated by applying fault tree.

In order to keep safety of well completion and long-term productivity, it is very necessary to build a fault tree to estimate the possibility of downhole accident. In addition, this fault tree can also be used as an accident pre-warning for a specific well completion method.

4.6 Discussion and summary

This chapter proposes a diagram framework of the selection system, and introduces the evaluation module in the system, which includes five influence factors, and each factor has several small indexes to provide a comprehensive evaluation. In addition, all the qualitative indexes can been quantified to make them can be utilized in this system. Finally, fault tree has been established to deal with risk index, and it can be integrated into the evaluation system, which will be discussed in chapter 5.

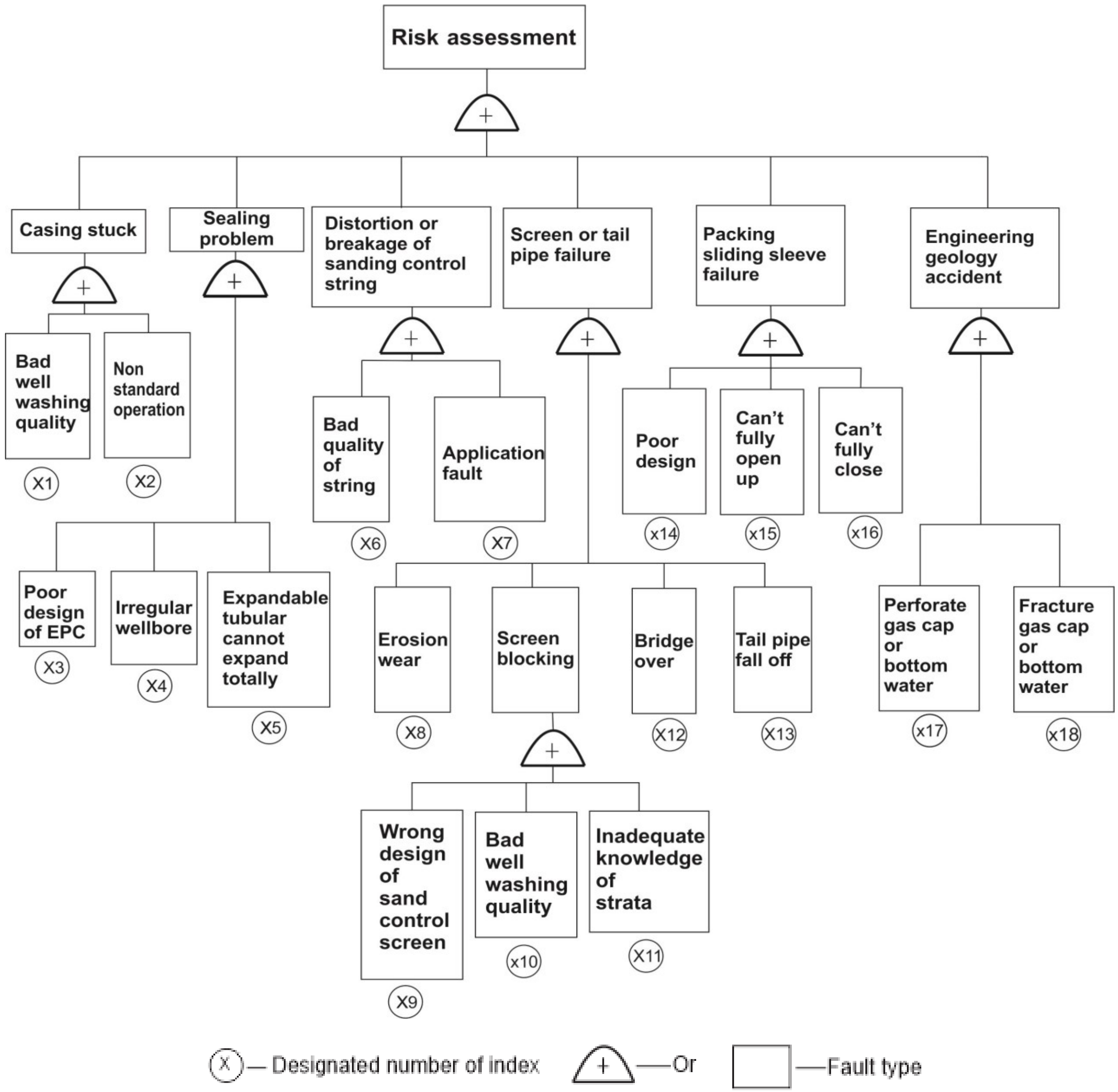


Figure 4. 5 Well completion method fault tree

Chapter 5 Feature-based optimum selection of well completion method

As introduced in chapter 4, there are lots of factors can influence the selection of well completion method, ranging from internal design factors to external factors. These factors not only have their own peculiarities but also correlate with each other, and their interactions constitute the major challenge for optimum selection system. Although these factors are all important to the system, they are in different levels in the evaluation model, and have different importance in this selection system. Therefore, it is important to establish a characteristic hierarchical structure and a calculation model to determine weights and final decision. AHP is a good way to build hierarchical structure, so this chapter describes how to apply improved AHP in this system. Section 5.1 describes arithmetic applied in the calculation model, which includes fuzzy complementary matrix, triangular fuzzy number, and fuzzy AHP. In addition, improvements for arithmetic described above are also represented. Section 5.2 describes well completion method feature, and how to build an optimum selection system based on this newly proposed feature. Section 5.3introduces calculation model of evaluation system. Section 5.4 represents the calculation model to select the best well completion method based on the proposed evaluation system.

5.1 Arithmetic

To better handle weight calculation in the selection system, some improvements for arithmetic have been made in this thesis, which can better conform to human being's thinking habit, and can make the result more accurate.

5.1.1 Triangular fuzzy number

When experts consider the relative importance between two indexes, they usually give some fuzzy values, and triangular fuzzy number is a good way to deal with fuzziness of human being's decision.

The judgement matrix is a crucial part in AHP, it can directly influence the final decision, so it is vital to construct a reasonable and accurate matrix. However, the traditional one to nine ranking scale method does not consider the fuzziness when people make judgement, it only represents two extreme cases: this index belongs to (degree of membership equals to 1) or not belong to (degree of membership equals to 0) this scale.

The membership degree of triangular fuzzy number is [111]

$$u_M(x) = \begin{cases} \frac{1}{m-l}x - \frac{1}{m-l}, x \in [l, m] \\ \frac{1}{m-u}x - \frac{u}{m-u}, x \in [m, u] \\ 0, x \in (-\infty, \mathrm{l}) \cup (u, +\infty) \end{cases} \tag{5.1}$$

Where l⩽m⩽u, l represents M's lower bound, m means the most probable value for M, and u represents M's upper bound. M becomes a non-fuzzy number when l=m=u. Generally, triangular fuzzy number is expressed as M= (l, m, u).

Assume M_1= (l_1, m_1, u_1), M2= (l_2, m_2, u_2) are triangular fuzzy numbers, the calculation equations between them are shown as below:

$$M_1 + M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{5.2}$$

$$M_1 - M_2 = (l_1 - l_2, m_1 - m_2, u_1 - u_2) \tag{5.3}$$

$$M_1 * M_2 = (l_1 * l_2, m_1 * m_2, u_1 * u_2) \tag{5.4}$$

Although 1-9 scale method is convenient and can be used in triangular fuzzy number, there are still some problems needed to be improved. First, judgement interval is too big. For example, fuzzy level 3= (1, 3, 5), then the fuzzy evaluation interval $e_{ij} = u_{ij} - l_{ij}$= 5-1=4, which is bigger than its mid-value. The value of *e* reflects the fuzzy degree and the reliability of this judgement, and if 1-9 scale method is adopted, then all judgements' reliabilities are going to be very low. The second point is the difference values between *l*, *m* and *u*, are the same, this is a big problem, because for the convenience of calculation, *l*, *m*, and *u* needed to be combined into one number to form a probability matrix B= $\left(b_{ij_{m*n}}\right)$. As shown in equation 5.5, b is always equal to *m*, and if the different values are the same, then the triangular fuzzy number is meaningless.

Because of these reasons, this thesis provides a new scale method and is shown in Table 5.1. This scale method provides three classifications of choice. The first one is applied when decision makers can confirm the difference of importance between two indexes and is sure about the

$$b_{ij} = \frac{l_{ij} + 4m_{ij} + u_{ij}}{6} \tag{5.5}$$

Table 5. 1 0.5-0.9 fuzzy scale method

Fuzzy number	Number scale	Meaning
0.5	(0.5,0.5,0.5)	Equally important
0.6	(0.5,0.6,0.7)	Weakly more important
0.7	(0.6,0.7,0.8)	Obviously more important
0.8	(0.7,0.8,0.9)	Strongly more important
0.9	(0.8,0.9,0.9)	Extremely more important
0.1	(0.1,0.1,0.2)	
0.2	(0.1,0,2,0.3)	
0.3	(0.2,0.3,0.4)	
0.4	(0.3,0.4,0.5)	
0.6+	(0.5,0.6,0.8)	Weakly more important
0.7+	(0.6,0.7,0.9)	Obviously more important
0.8+	(0.8,0.8,0.9)	Strongly more important
0.9+	(0.8,0.9,1.0)	Extremely more important
0.1+	(0.0,0.1,0.2)	
0.2+	(0.2,0,2,0.1)	
0.3+	(0.1,0.3,0.4)	
0.4+	(0.2,0.4,0.5)	
0.6-	(0.5,0.6,0.6)	Weakly more important
0.7-	(0.5,0.7,0.8)	Obviously more important
0.8-	(0.6,0.8,0.9)	Strongly more important
0.9-	(0.7,0.9,0.9)	Extremely more important
0.1-	(0.1,0.1,0.3)	
0.2-	(0.1,0,2,0.4)	
0.3-	(0.2,0.3,0.5)	
0.4-	(0.4,0.4,0.5)	

judgement. The second class is the fuzzy number with +, this class is useful when a decision maker thinks A is more than weakly more important than B, but cannot achieve the obviously more important level, then 0.6+ is a good choice under this situation. The third class is the fuzzy number with -, and like 0.7-, it indicates that the decision maker thinks A is very close but cannot achieve the obviously more important level. This new scale method is not only easy to be applied, but also can better deal with the fuzziness exists in human being's thinking habit. It is more flexible and can avoid those two problems mentioned above. In addition, this new method can better meet the requirement of fuzzy matrix because of definition 1 shown in next section.

5.1.2 Fuzzy complementary matrix

In AHP, there are usually two kinds of judgement matrix, one is complementary matrix, the other is called reciprocal matrix, and complementary matrix is adopted in this thesis to determine weight. Some definitions needed to be declared first.

Definition 1: Suppose $A = (a_{ij})_{n*n}$ is a judgement matrix given by a decision-maker, if this matrix satisfied equation 5.6, then A is called fuzzy matrix.

$$0 \leq a_{ij} \leq 1, i = 1,2, \ldots, n; j = 1,2, \ldots., n \tag{5.6}$$

Definition 2: Suppose $A = (a_{ij})_{n*n}$ is a fuzzy judgement matrix, $r_{ij} = (l_{ij}, m_{ij}, u_{ij})$ is a triangular fuzzy number belongs to A, and $0 \leq l_{ij} \leq m_{ij} \leq u_{ij} \leq 1$; i, j= $1,2, \ldots, n$, if the matrix satisfied equation 5.7 and 5.8, then A is called fuzzy complementary matrix.

$$l_{ii} = m_{ii} = u_{ii} = 0.5, i = 1,2, \ldots, n \tag{5.7}$$

$$l_{ij} + u_{ji} = 1, m_{ij} + m_{ji} = 1, u_{ij} + l_{ji} = 1, i \neq j;\ i, j = 1,2, \ldots, n \tag{5.8}$$

The fundamental difference between complementary matrix and other regular matrix is there is a fuzzy evaluation interval $e_{ij} = u_{ij} - l_{ij}$ for each index, and this interval represents the reliability of expert judgement, which can also be interpreted as "confidence interval" in mathematical statistics. Large e_{ij} represents small reliability, and this reliability can be utilized to reflect the influence of uncertainty on final results.

5.1.3 Consistence of fuzzy AHP

As discussed before, consistency is an important factor in AHP, inconsistent matrix represents logical error and the whole matrix needed to be adjusted, so it is necessary to check the consistency.

The most commonly used method to check consistency is to make sure CR<0.1, however, this method is based on experience, and is not accurate enough. Therefore, instead of using CR, this

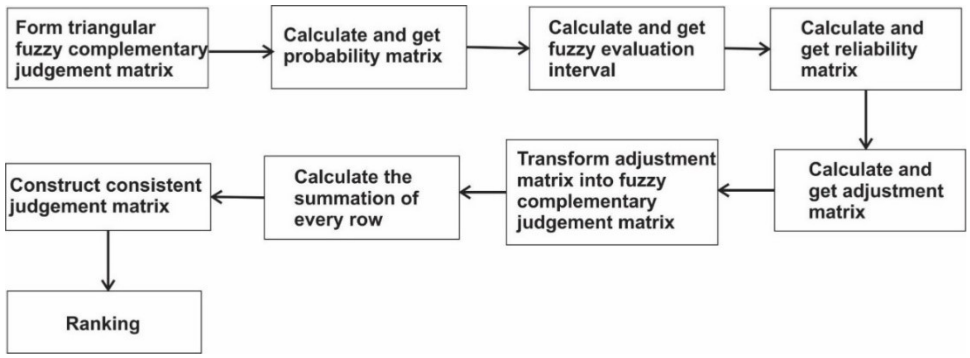


Figure 5. 1 Flow chart of constructing consistent judgement matrix

thesis employs a series of transformation to change the original judgement matrix into a consistent matrix, shown in figure 5.1. If the final importance ranking shown in the consistent matrix is different from the original matrix, it usually represents that there are logical conflicts exist in the original matrix, and they needed to be corrected.

5.2 Selection framework and well completion method feature

Chapter 3 introduces four well completion methods of vertical well and six of horizontal well, however, there are more well completion methods exist in oil industry, some are uncommon methods, some are newly proposed, and more and more methods will be invented in the future.
Therefore, in order to improve the expansibility of this selection system, a well completion method feature is proposed in this thesis. This feature describes well completion method by defining attributes, parameters and methods to make any well method can be fitted in this selection system. In addition, this feature makes well completion methods represented in a computer interpretable data structure, each method can be considered as an instance of this well completion method feature. As shown in Figure 5.2, this feature is a class that can be used to describe all kinds of well completion methods by generating their instances with different attribute values. Using the feature modelling approach, different well completion methods can be described in well-organized way, and the system model can be easily expanded to include new well completion method. Figure 5.3 shows the relationship between three modules

and their relationships in this system, it also shows how this new feature helps with the selection of well completion method.

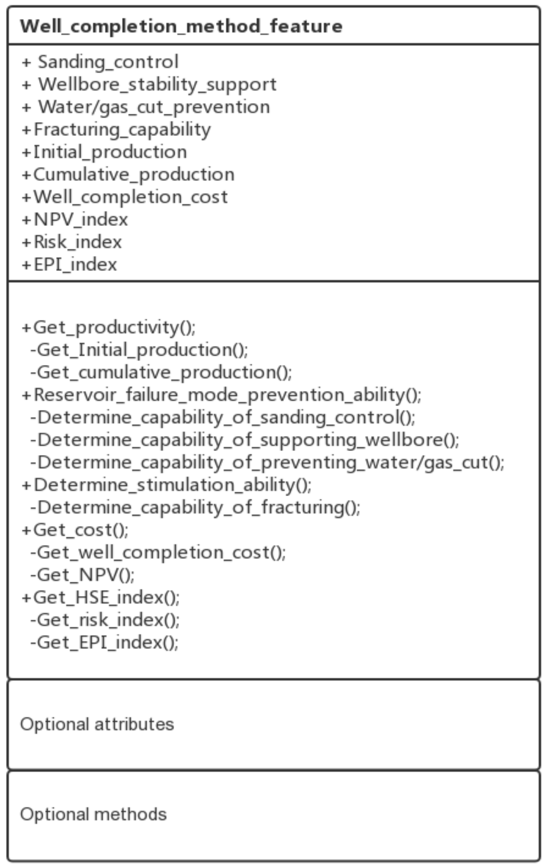


Figure 5. 2 Definition of well completion feature

The optimum selection system is built based on well completion method feature, which includes three modules: information module, evaluation module, and optimum well completion selection module.

As shown in Figure 5.4, these three modules are connected with each other. Input module includes reservoir information, oil production database, and economical database, they are the database of whole system, and users need to provide and input these data in the system. Reservoir information contains both qualitative and quantitative data, and as shown in chapter 4, all the qualitative data have been quantified and can be used by this system. Evaluation module utilizes data from input module to calculate corresponding criteria, and MADM model is applied in this step. Then the selection module considers influence factors from five perspectives to select the most reasonable method from the well completion methods class.

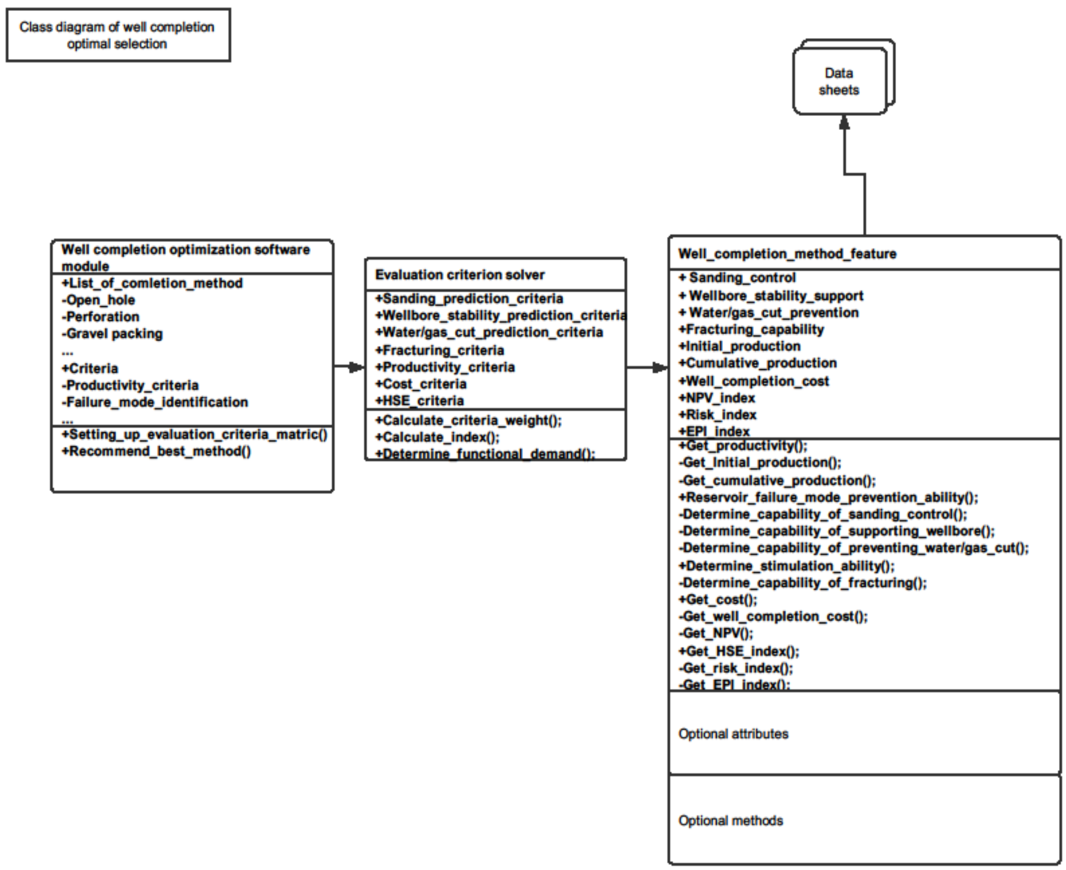


Figure 5. 3 Class diagram of well completion optimal selection

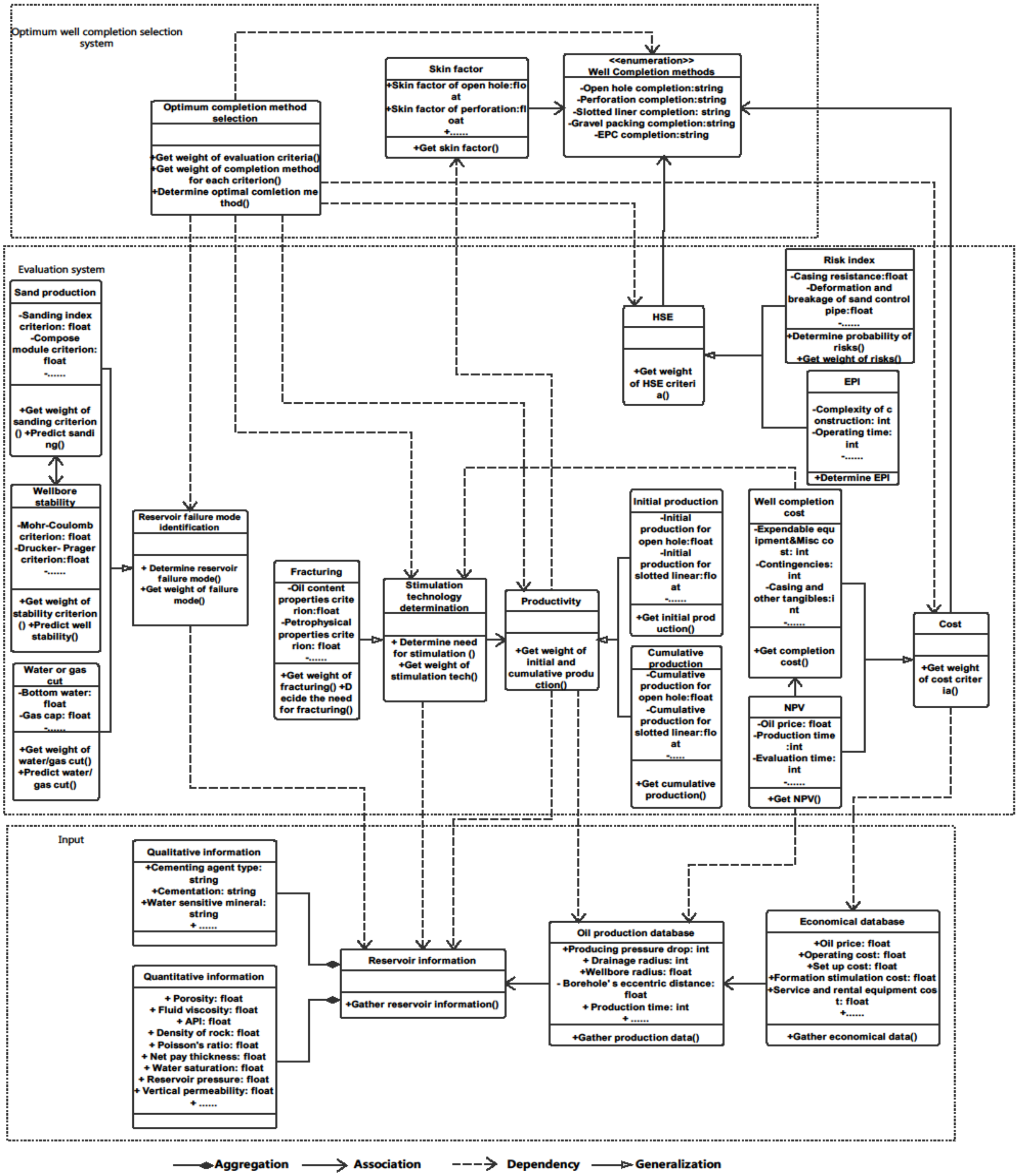


Figure 5. 4 UML framework of optimum well completion method system

5.3 Calculation model of the evaluation module

Evaluation module can be mainly divided into two components. The first component (Ⅰ) includes reservoir failure mode identification and stimulation technology determination, this part only needs data from reservoir information class, and well completion methods cannot influence outcome in this part. The second component (Ⅱ) includes productivity, cost and HSE evaluation. The results from this component is directly generated from well completion methods, which means different well completion methods lead to different values on these factors. The way to deal with these two components are different, therefore, two calculation models are introduced in this section.

5.3.1 Calculation model for component (Ⅰ)

component (Ⅰ) includes reservoir failure mode identification and stimulation technology determination. There are three sub-factors in failure mode, one sub-factor in stimulation technology. These sub-factors are not controlled by well completion methods and are only influenced by reservoir information, so the characteristics of calculation model for this part are:

- Although sub-factors like sand production, wellbore stability and water/gas cut belong to reservoir failure mode identification factor, there is no need to determine weight for these three sub-factors.
- Each sub-factor has several judgement criteria. Because these criteria solve the problem from different perspectives and use different data, and an oil company may do not have all the data or some data are not accurate enough, so it is necessary to assign weight to each criterion to improve the precision of system.
- Reservoir failure mode identification factor and stimulation technology determination factor are not included in the final AHP selection system.

The calculation model for part one is displayed by calculating sand production as an example. Because there are 10 criteria and pairwise comparison is required, so it is easy to cause inconsistency due to logical error, therefore, 10 criteria are divided into three groups, and the hierarchy chart is shown in Figure 5.5.

Table 5. 2 Classification of sanding judgement criteria

Name of second level criteria	Symbol	Name of lower level criteria	Symbol
Reservoir information	D1	Type of cement	C1
		Type of cementation	C2
		Porosity	C3
		Water-sensitive minerals	C6
Properties of petroleum	D2	API	C5
		Fluid viscosity	C4
Empirical formulas	D3	Compose module method	C7
		SLB method	C8
		Sanding index method	C9
		Compressive strength method	C10

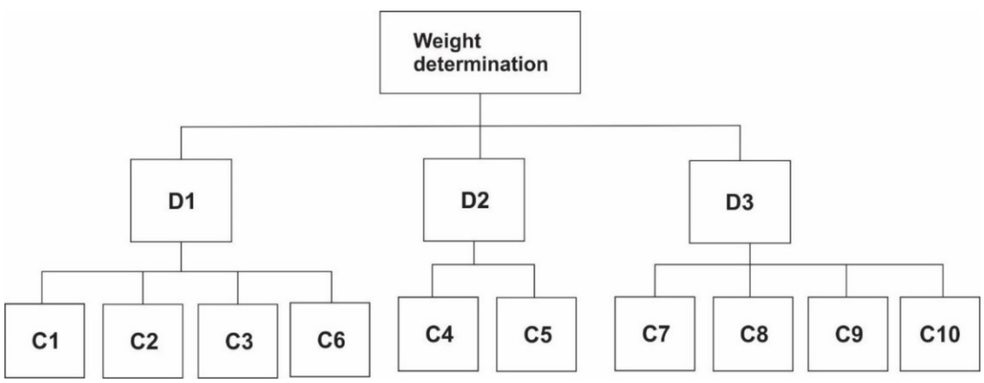


Figure 5. 5 Hierarchy chart of sand production

Step 1: Build fuzzy triangular complementary matrix A $= (a_{ij})_{n*n}$ for second level.

D2 is weakly more important than D1 (0.6), D3 is extremely more important than D1 (0.9), and D3 is strongly more important than D2 (0.8+).

Table 5. 3 Fuzzy triangular complementary matrix for second level

	D1			D2			D3		
D1	0.500	0.500	0.500	0.300	0.400	0.500	0.100	0.100	0.200
D2	0.500	0.600	0.700	0.500	0.500	0.500	0.100	0.200	0.200
D3	0.800	0.900	0.900	0.800	0.800	0.900	0.500	0.500	0.500

Step 2: Build probability matrix B $= (b_{ij})_{n*n}$ for second level.

$$b_{ij} = \frac{l_{ij} + 4m_{ij} + u_{ij}}{6} \quad (5.9)$$

Table 5. 4 Probability matrix for second level

	D1	D2	D3
D1	0.500	0.400	0.117
D2	0.600	0.500	0.183
D3	0.883	0.817	0.500

Step 3: Determine judgement interval e_{ij}.

$$e_{ij=u_{ij}-l_{ij}} \quad (5.10)$$

Table 5. 5 Judgement interval for second level

	D1	D2	D3
D1	0.000	0.200	0.100
D2	0.200	0.000	0.100
D3	0.100	0.100	0.000

Step 4: Determine reliability matrix $S = (s_{ij})_{n*n}$ for second level.

$$s_{ij} = 1 - \frac{e_{ij}}{2 * (l_{ij} + m_{ij} + u_{ij})} \quad (5.11)$$

Table 5. 6 Reliability matrix for second level

	D1	D2	D3
D1	1.000	0.917	0.875
D2	0.944	1.000	0.900
D3	0.981	0.980	1.000

Step 5: Determine adjustment matrix $T = (t_{ij})_{n*n}$ for second level.

$$T = B * S = (b_{ij} * s_{ij})_{n*n} \quad (5.12)$$

Table 5. 7 Adjustment matrix for second level

	D1	D2	D3
D1	0.500	0.367	0.102
D2	0.567	0.500	0.165

D3	0.866	0.800	0.500

Step 6: Transform adjustment matrix into fuzzy complementary judgement matrix R = $(r_{ij})_{n*n}$.

$$r_{ij} = \frac{1 + t_{ij} - t_{ji}}{2} \quad (5.13)$$

Table 5. 8 New fuzzy complementary matrix for second level

	D1	D2	D3
D1	0.500	0.400	0.118
D2	0.600	0.500	0.182
D3	0.882	0.818	0.500

Step 7: Calculate summation of each row P_i.

$$P_{i=}r_{i1} + r_{i2} + .. + r_{ij} \quad (5.14)$$

Table 5. 9 Summation of each row

P1	1.018
P2	1.282
P3	2.200

Step 8: Construct fuzzy consistent matrix C = $(c_{ij})_{n*n}$.

$$c_{ij} = \frac{P_i - P_j}{2 * (n-1)} + 0.5 \quad (5.15)$$

Table 5. 10 Fuzzy consistent matrix for second level

	D1	D2	D3
D1	0.500	0.434	0.205
D2	0.566	0.500	0.271
D3	0.795	0.729	0.500

Step 9: Ranking for second level w_i.

$$w_i = \frac{1}{n} - \frac{1}{2 * \alpha} + \frac{1}{n * \alpha}\sum_{k=1}^{n} a_{ik}, i = 1,2, \dots, n \quad (5.16)$$

$$\alpha = \frac{n-1}{2}$$

Table 5. 11 Ranking for second level

D1	0.213
D2	0.279
D3	0.508

Step 10: Build fuzzy triangular complementary matrix A = $(a_{ij})_{n*n}$ for lower level.

D1: C1, C2 and C6 are equally important to each other (0.5); C1 is weakly more important than C3 (0.6+); C2 is weakly more important than C3 (0.6); C3 is weakly more important than C6 (0.6+).

D2: C4 is weakly more important than C5 (0.6).

D3: C7, C8 and C10 are equally important to each other (0.5); C7 is weakly more important than C9 (0.6+); C8 is weakly more important than C9 (0.6); C10 is weakly more important than C9 (0.6);

Table 5. 12 Fuzzy triangular complementary matrix for lower level

		C1			C2			C3			C6		
D1	C1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.8	0.5	0.5	0.5
	C2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.5	0.5	0.5
	C3	0.2	0.4	0.5	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.6	0.8
	C6	0.5	0.5	0.5	0.5	0.5	0.5	0.2	0.4	0.5	0.5	0.5	0.5

		C4			C5		
D2	C4	0.5	0.5	0.5	0.5	0.6	0.7
	C5	0.3	0.4	0.5	0.5	0.5	0.5

		C7			C8			C9			C10		
D3	C7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.8	0.5	0.5	0.5
	C8	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.5	0.5	0.5
	C9	0.2	0.4	0.5	0.3	0.4	0.5	0.5	0.5	0.5	0.3	0.4	0.5
	C10	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.7	0.5	0.5	0.5

Step 11: Build probability matrix B = $(b_{ij})_{n*n}$ for lower level.

Table 5. 13 Probability matrix for lower level

		C1	C2	C3	C6

D1	C1	0.500	0.500	0.617	0.500
	C2	0.500	0.500	0.600	0.500
	C3	0.383	0.400	0.500	0.617
	C6	0.500	0.500	0.383	0.500

D2		C4	C5
	C4	0.500	0.600
	C5	0.400	0.500

D3		C7	C8	C9	C10
	C7	0.500	0.500	0.617	0.500
	C8	0.500	0.500	0.600	0.500
	C9	0.383	0.400	0.500	0.400
	C10	0.500	0.500	0.600	0.500

Step 12: Determine judgement interval e_{ij}.

Table 5. 14 Judgement interval for lower level

D1		C1	C2	C3	C6
	C1	0.000	0.000	0.300	0.000
	C2	0.000	0.000	0.200	0.000
	C3	0.300	0.200	0.000	0.300
	C6	0.000	0.000	0.300	0.000

D2		C4	C5
	C4	0.000	0.200
	C5	0.200	0.000

D3		C7	C8	C9	C10
	C7	0.000	0.000	0.300	0.000
	C8	0.000	0.000	0.200	0.000
	C9	0.300	0.200	0.000	0.200
	C10	0.000	0.000	0.200	0.000

Step 13: Determine reliability matrix $S = (s_{ij})_{n*n}$ for lower level.

Table 5. 15 Reliability matrix for lower level

D1		C1	C2	C3	C6
	C1	1.000	1.000	0.921	1.000
	C2	1.000	1.000	0.944	1.000

	C3	0.864	0.917	0.000	0.921
	C6	1.000	1.000	0.864	1.000

		C4	C5
D2	C4	1.000	0.933
	C5	0.917	1.000

		C7	C8	C9	C10
D3	C7	1.000	1.000	0.921	1.000
	C8	1.000	1.000	0.944	1.000
	C9	0.864	0.917	1.000	0.917
	C10	1.000	1.000	0.944	1.000

Step 14: Determine adjustment matrix $T = (t_{ij})_{n*n}$ for lower level.

Table 5. 16 Adjustment matrix for lower level

		C1	C2	C3	C6
D1	C1	0.500	0.500	0.568	0.500
	C2	0.500	0.500	0.567	0.500
	C3	0.331	0.367	0.500	0.568
	C6	0.500	0.500	0.331	0.500

		C4	C5
D2	C4	0.500	0.560
	C5	0.367	0.500

		C7	C8	C9	C10
D3	C7	0.500	0.500	0.568	0.500
	C8	0.500	0.500	0.567	0.500
	C9	0.331	0.367	0.500	0.367
	C10	0.500	0.500	0.567	0.500

Step 15: Transform adjustment matrix into fuzzy complementary judgement matrix $R = (r_{ij})_{n*n}$.

Table 5. 17 New fuzzy complementary matrix for lower level

		C1	C2	C3	C6	P_i
D1	C1	0.500	0.500	0.618	0.500	2.118
	C2	0.500	0.500	0.600	0.500	2.100
	C3	0.382	0.400	0.500	0.618	1.900
	C6	0.500	0.500	0.382	0.500	1.882

D2		C4	C5	P_i
	C4	0.500	0.597	1.097
	C5	0.403	0.500	0.903

D3		C7	C8	C9	C10	P_i
	C7	0.500	0.500	0.618	0.500	2.118
	C8	0.500	0.500	0.600	0.500	2.100
	C9	0.382	0.400	0.500	0.400	1.682
	C10	0.500	0.500	0.600	0.500	2.100

Step 16: Construct fuzzy consistent matrix $C = (c_{ij})_{n*n}$.

Table 5. 18 Fuzzy consistent matrix for lower level

D1		C1	C2	C3	C6
	C1	0.500	0.503	0.536	0.539
	C2	0.497	0.500	0.533	0.536
	C3	0.464	0.467	0.500	0.503
	C6	0.461	0.464	0.497	0.500

D2		C4	C5
	C4	0.500	0.597
	C5	0.403	0.500

D3		C7	C8	C9	C10
	C7	0.500	0.503	0.573	0.503
	C8	0.497	0.500	0.570	0.500
	C9	0.427	0.430	0.500	0.430
	C10	0.497	0.500	0.570	0.500

Step 17: Ranking of lower level w_i.

Table 5. 19 Ranking for lower level

D1	C1	C2	C3	C6
	0.263	0.261	0.239	0.237

D2	C4	C5
	0.597	0.403

D3	C7	C8	C9	C10
	0.263	0.261	0.215	0.261

Step 19: Calculate absolute weights of criteria.

$$\text{Absolute weight} = \text{Weight of lower level's criteria} * \text{corresponding weight of sedond level}$$

Table 5. 20 Absolute weights of criteria

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
0.056	0.056	0.051	0.166	0.112	0.050	0.134	0.133	0.109	0.133

Step 20: Get results of each criteria, then multiply these results with corresponding absolute weight to get weighted results W_i.

Step 21: Sum up the weight results W_i to get a result F.

Step 22: Compare F with criterion of failure mode (Table 5.21) to identify failure mode.

Table 5. 21 Judgement criteria of failure mode

Name	Criteria	Result
Sand production	$F \geqslant 0.5$	Sand control is needed
Wellbore stability	$F \geqslant 0.5$	Wellbore support is needed
Water/gas cut	$F \geqslant 0.5$	Water/gas layer separated is needed

5.3.2 Calculation model for component (Ⅱ)

Part two includes productivity, cost, HSE and their corresponding sub-factors. Weights in part one can help different companies or oilfields to determine failure modes and demand of stimulation based on their own data sources and situations, so the weights assigning process is mainly controlled by human beings, and the weights in part one is determined by a subjective method. The influence factors in part two are directly controlled by well completion methods, and weights in this part is used to determine factors' degree of importance for the final decision, however, sometimes it is hard to decide which part is more important, for example, more productivity or less cost?

Objective weight determination method is a good way to deal with this situation, and entropy method is adopted in this system, the evaluation matrix in entropy method is formed by real data, which cuts off the subjectivity and makes weights assigning process totally objective. However, this method has an inevitable disadvantage, which is the weights determined by this method may contradict with actual situation. This is because in the process of MODM, attribute values of the most important index may do not have a big difference between alternatives, and the least important index may can lead to a big value difference, therefore, important factor may have a small weight. Based on the situation described above, the idea of combining subjective weight determination with objective weight determination is put forward in this thesis.

Assume j is an evaluation index, a_j is its weight determined by objective method, and b_j is its weight determined by subjective method. The final weight j can be calculation as follow, and the core of this method is how to determine α.

$$w_j = \alpha * a_j + (1 - \alpha) * b_j \tag{5.17}$$

In this method, a concept called the grade of evaluation index (P_1, P_2, …, P_k) is proposed. The importance degree of this grade is P_1>P_2…> P_k, it means the evaluation index in P_k-1 is more important than index in P_k. Each grade includes several evaluation indexes, and these indexes also have sequence with their grade.

Main contents of this new weight determination method are:

- If evaluation indexes do not have any essential distinction, this means they are in the same grade, then weights can be totally determined by objective method, α =1.
- If evaluation indexes are in different grades, but the rank of weights determined by subjective method is the same as objective method, then it represents important indexes do get bigger weight, so in order to eliminate influence caused by subjective factor, the weights determined by objective method is set as the final weights, α =1.
- If evaluation indexes are in different grades, and the rank of weights determined by subjective method is the different from objective method, but the rank of grade is the same, then α =0.5, which is set average values as the final weight.
- If evaluation indexes are in different grades, the rank of weights determined by subjective method is different from objective method, and the rank of grade is also different, then it represents the weights determined by objective method is contradict with reality and should

not be considered. Therefore, weights determined by subjective method is set as the final weights under this situation, α =0.

- It is a special case when a weight determined by objective method is 0, this situation represents every alternative has the same value for this index, then this index is useless for ranking and decision making, so this index should be eliminated first before using this new weighting determination method.

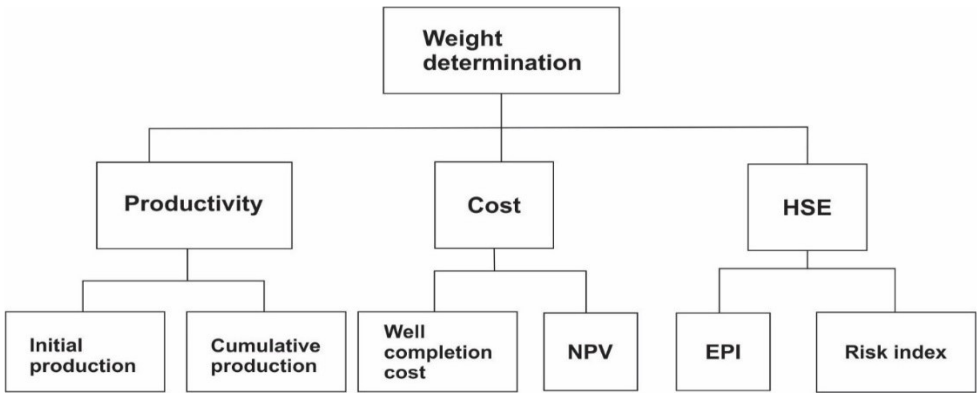


Figure 5. 6 Hierarchy chart of part two

The hierarchy chart of part two is shown in Figure 5.6, and the calculation model for part two is shown as follows.

Step 1: Build fuzzy triangular complementary matrix $A = (a_{ij})_{n*n}$ for second level based on human being's judgement, and then get weights for second level factors.

Step 2: Build fuzzy triangular complementary matrix $A' = (a_{ij}')_{n*n}$ for lower level based on human being's judgement, and then get weights for lower level factors.

Step 3: Multiplying second level factor's weights by lower level factor's weights to get absolute weights for lower level factors.

Step 4: Construct judgement matrix $X = (x_{ij})_{m*n}$based on original data.

Step 5: Apply dimensionless method on judgement matrix.

The bigger the better indexes: $v_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$ (5.18)

The smaller the better indexes: $v_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}$ (5.19)

Step 6: Calculate indexes' weight p_{ij} of each alternative.

$$p_{ij} = v_{ij} / \sum_{i=1}^{m} v_{ij} \tag{5.20}$$

Step 7: Determine entropy e_j of each index.

$$e_j = -1/\ln(m) \sum_{i=1}^{m} p_{ij} * lnp_{ij} \tag{5.21}$$

Step 8: Determine variation coefficient D_j of each index.

$$D_j = 1 - e_j \tag{5.22}$$

Step 9: Calculate entropy weight w_j of each index.

$$w_j = d_j / \sum_{j=1}^{n} d_j \tag{5.23}$$

Step 10: Determine grade of evaluation indexes and calculate the final weights F_j according to the new weights determination method.

5.4 Optimum selection model of well completion methods

The evaluation system has been established and weights can also be determined, but functions and parameters for different types of well completion methods are still needed to be set, and selection model is needed to be built to finish the optimum selection.

5.4.1 Functions and parameters of different well completion methods

This system includes 7 kinds of well completion method, and the functions needed to be considered are: whether it can control sand, whether it can support wellbore, whether it can isolate layers, and whether it can be used to apply stimulation technology. Well completion methods' functions are summarized and shown in Table 5.22

Table 5. 22 Well completion methods' functions summarization

	Sand control	Wellbore support	Layer isolation	Stimulation
Open hole	×	×	×	×
Cased hole	×	√	√	√
Slotted linear	√	√	×	×
Slotted liner with ECP	√	√	√	√
Open-hole gravel pack	√	√	×	×
Cased hole gravel pack	√	√	√	√
Expandable tubular well	√	√	×	×

As for evaluation values of different well completion methods, productivity and cost can be calculated directly with the formulas given above, and this section mainly discusses HSE indexes. The judgement criteria of EPI have been given, so well completion methods' EPI can be determined and shown in Table 5.23.

Table 5. 23 Well completion methods' EPI value

Well completion method	EPI value
Open hole	1
Cased hole	8
Slotted liner	4.5
Slotted liner with ECP	5
Open-hole gravel pack	6
Cased hole gravel pack	9
Expandable tubular	5

Fault tree has been established above, and cut sets for different well completion methods are:

Open hole: {X1, X2};

Cased hole: {X1, X2, X12, X13, X17, X18};

Slotted liner: {X6, X7, X8, X9, X10, X11, X12, X13};

Slotted liner with EPC: {X3, X4, X6, X7, X8, X9, X10, X11, X12, X13};

Open-hole gravel pack: {X1, X2, X10, X11, X12, X14, X15, X16};

Cased hole gravel pack: {X1, X2, X10, X11, X12, X13, X14, X15, X16, X17, X18};

Expandable tubular: {X4, X5, X6, X7, X8, X9, X10, X11, X12, X13}.

The basic events above are all independent with each other and their probabilities are all 0.1, then according to the calculation formula of fault tree, the risk probabilities of well completion methods can be calculated, and the outcome is shown in Table 5.24.

Table 5. 24 Risk probability of well completion methods

Well completion methods	Risk probability
Open hole	0.19
Cased hole	0.47
Slotted liner	0.57
Slotted liner with ECP	0.65
Open-hole gravel pack	0.57
Cased hole gravel pack	0.69
Expandable tubular	0.65

5.4.2 Well completion method selection model

As shown in Figure 5.7, the whole well completion method selection model can be divided into two parts, the first part is to determine failure mode and stimulation requirement to select appropriate well completion methods, which can make sure the success of producing. The second part tries to select the optimum well completion method by considering problem from three perspectives at the same time.

In the first part, fuzzy AHP of MADM is used to determine weights of different criteria. Because weight is included in this system, so companies can give different weight on criteria based on their own situation and accuracy of data. In the second part, a newly proposed weights determination system is used to calculate weights, which includes both subjective and objective methods. Then the final decision can be both objective and includes the preference of decision makers. This system enables expert teams to reach consensus on the qualitative and quantitative values to ultimately make optimum selection.

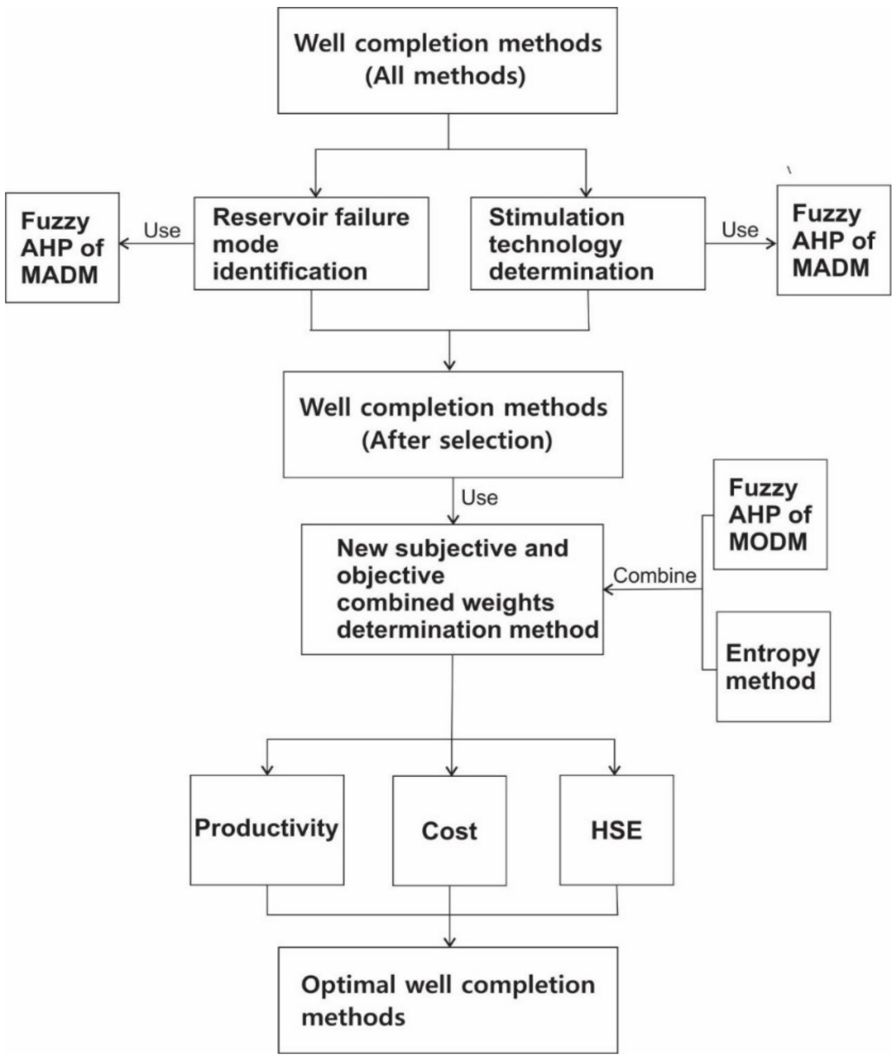


Figure 5. 7 Well completion methods selection model

Chapter 6: Case study 1-Heavy oil extraction in Christina Lake

This chapter utilizes data of a well in the Christina Lake area, which is located in the southern Athabasca oil-sands area to demonstrate the feasibility of proposed well completion selection system. Because not all the data can be obtained exactly from one well, so the data used in case study will be divided into three types, and they will be distinguished by different font. The first type is called accurate data, the second kind is reference data, which are data from adjoining wells or wells located in the same reservoir, and they will be shown in boldface. The last type is data estimated based on reservoir's condition, and they will be italicized.

6.1 Reservoir failure mode identification

This section describes how to identify reservoir's failure mode by using the new proposed method.

6.1.1 Sanding

The data used to determine sanding is shown in Table 6.1, and their related weights are calculated in chapter 5.

Table 6. 1 Data used for sanding determination

Cementing agents	Argillaceous cement
Type of cementation	Contact cementation
Porosity	30%
In-place fluid viscosity(cp)	300000 cp
API	**8.5** [112]
Water-sensitive minerals	Include montmorillonite, illite, smectite or chlorite
Density of rock (g/cm^3)	2.1
Compressional wave slowness (μs/m)	480
Poisson ratio	**0.25** [113]
Young's modulus (10^4 MPa)	0.5
Transverse interval transit time (μs/m)	*626 (estimated)*

FBHP (MPa)	2.2
Gravity of acceleration (m/s^2)	10
Reservoir pressure (MPa)	2.6
Depth of reservoir (m)	375
Compressive strength of rock (MPa)	*11.23*

Then according to the judgement criteria mentioned in chapter 4, we can get quantitative values of each criterion, which is shown in Table 6.2.

Table 6. 2 Quantitative values of sanding judgement criteria

Name of criterion	Quantitative value
Cementing agent	1
Cementation	1
Porosity	0.7
Fluid viscosity	1
API	1
Water-sensitive minerals	1
Compose module method=9059.89	1
SLB method=1.14*10^7	1
Sanding index method=0.33*10^4	1
Compressive strength method=14.87	1

The absolute weight of each criterion is shown in Table 5.20, which can be adjusted based on oil companies' own situation. Then the final result can be calculated by multiplying quantitative values by absolute weight.

The result is equal to 0.985, which is larger than 0.5, so this well has very high probability of sanding. And the suitable well completion methods under this situation are slotted linear, slotted liner with ECP, Open-hole gravel pack, cased hole gravel pack, and expandable tubular well completion methods.

6.1.2 Wellbore stability

The data used to determine wellbore stability is shown in Table 6.3. Because Mohr-Coulomb criterion does not consider σ_2, so some researchers think it is not accurate enough, therefore, the weight assignment is 0.4 for Mohr-Coulomb criterion and 0.6 for Drucker-Prager criterion.

Table 6. 3 Data used for wellbore stability determination

Name of criterion	Quantitative value
Minimum effective principal stresses, Mpa	*6.375*
Maximum effective principal stresses, Mpa	*10.5*
Cohesive strength, Mpa	*0.47*
Friction angle	*34*
Biot poroelastic constant	0.9
Pore pressure	3.74

Table 6. 4 Quantitative values of wellbore stability judgement criteria

Name of criterion	Quantitative value
Mohr-Coulomb criterion	0
Drucker-Prager criterion	1

The result is equal to 0.6, which means this well may have the instable problem, and the well completion method should be equipped with the ability to support it. And the suitable well completion methods under this situation are slotted linear, slotted liner with ECP, Open-hole gravel pack, cased hole gravel pack, and expandable tubular well completion methods.

6.1.3 Water/ gas cut

This reservoir has around 1.5m bottom water zone, so there is a possibility of water cut, which means only slotted liner with ECP and cased hole gravel pack well completion methods are left after selection.

In addition, because stimulation techniques can be applied on both of these two methods, so there is no necessary to check the demand of stimulation.

6.2 Productivity, cost, and HSE indexes

6.2.1 Quantitative values of indexes

Evaluation matrix needs to be established first before determining final weight, which includes initial production, cumulative production, well completion cost, NPV, EPI, and risk index.

Table 6.5 shows the data required for calculating productivity and cost, and Table 6.6 shows the possible productivity of slotted liner with ECP and cased hole gravel pack well completion methods.

Table 6. 5 Data used for productivity and cost determination

Name of criterion	Quantitative value
Horizontal permeability, μm^2	**4.935** [114]
Vertical permeability, μm^2	3.356
Anisotropy coefficient	1.372
Borehole' s eccentric distance, m	0
Oil formation volume factor	1.015
Pay zone, m	10
Drainage radius, m	160
Horizontal well length, m	*500*
Fluid viscosity, mPa·s	2000
Wellbore radius, m	*0.1079*
Skin factor of CHGP	*2.87* [69]
Skin factor of slotted liner with ECP	*14.59* [115]

Table 6. 6 Quantitative values of productivity

	Initial production, m^3/d	cumulative production, m^3, t=90
CHGP	23.16	4052.99
Slotted liner with ECP	14.25	2533.12

Then the evaluation conclusive table can be established and shown in Table 6.7.

Table 6. 7 Summative table of evaluation indexes

	Initial pro	Cumulative pro	Well Completion cost ($) [69]	NPV (C$) T=16 years	EPI	Risk index
CHGP	23.16	4052.99	*10879000*	*4300.07*	9	0.69
SL(ECP)	14.25	2533.12	*8491000*	*3228.35*	5	0.65

Then the evaluation indexes matrix can be gotten and shown as follows.

$$A = \begin{bmatrix} 23.158 & 4052.985 & 10879000 & 4300.07 & 9 & 0.69 \\ 14.250 & 2533.116 & 8491000 & 3228.35 & 5 & 0.65 \end{bmatrix}$$

There are two kinds of indexes within this evaluation system, the first kind includes initial productivity, cumulative productivity and NPV, they are the bigger the better indexes. The second kind is called the smaller the better indexes, which includes well completion cost, EPI and risk index. Then based on equation 5.18 and 5,19, the next step is to apply dimensionless method on judgement matrix, and B is the matrix after normalized.

$$B = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix}$$

6.2.2 Weight determination

a. Fuzzy AHP method

Assume the preference grade of evaluation indexes is HSE>Productivity>Cost. Fuzzy triangular complementary matrix $A = (a_{ij})_{n*n}$ for second level is built and shown in Table 6.8. HSE is weakly more important than productivity (0.6+), productivity is obviously more important than cost (0.7+), and HSE is strongly more important than cost (0.8).

And the rank of second level criteria is shown in Table 6.9.

Table 6. 8 Fuzzy triangular complementary matrix for second level

	HSE			Cost			Productivity		
HSE	0.500	0.500	0.500	0.700	0.800	0.900	0.500	0.600	0.800
Cost	0.100	0.200	0.300	0.500	0.500	0.500	0.100	0.300	0.400
Productivity	0.200	0.400	0.500	0.600	0.700	0.900	0.500	0.500	0.500

Table 6. 9 Ranking for second level

HSE	Cost	Productivity
0.438	0.204	0.358

The next step is to build fuzzy triangular complementary matrix for lower level, which is shown in Table 6.10, and the rank of lower level is shown in Table 6.11.

- Productivity: Cumulative productivity is obviously more important (0.7) than initial productivity.

- Cost: NPV is weakly more important (0.6) than well completion cost.
- HSE: Risk index is weakly more important (0.6+) than EPI.

Table 6. 10 Fuzzy triangular complementary matrix for lower level

	Cumulative pro			Initial pro		
Cumulative pro	0.500	0.500	0.500	0.600	0.700	0.800
Initial pro	0.200	0.300	0.400	0.500	0.500	0.500

	Well completion cost			NPV		
Well completion cost	0.500	0.500	0.500	0.300	0.400	0.500
NPV	0.500	0.600	0.700	0.500	0.500	0.500

	Risk index			EPI		
Risk index	0.500	0.500	0.500	0.500	0.600	0.800
EPI	0.200	0.400	0.500	0.500	0.500	0.500

Table 6. 11 Ranking for lower level for lower level

Cumulative pro	Initial pro
0.693	0.307

Well completion cost	NPV
0.403	0.597

Risk index	EPI
0.612	0.388

$$\text{Absolute weight} = \text{Weight of lower level's criteria} * \text{corresponding weight of sedond level}$$

Table 6. 12 Absolute weights of criteria

Initial productivity	0.1099
Cumulative productivity	0.2485
Well completion cost	0.0821
NPV	0.1215
EPI	0.1699
Risk index	0.2680

b. Entropy method

Because evaluation indexes' differences between two well completion methods are same, so the weights determined by entropy method would be productivity=cost=HSE, which means the rank of grade is contradict with reality, and entropy method should not be considered in this case.

6.2.3 Well completion method determination

Based on absolute weights and evaluation indexes' matrix, the final points of slotted liner with ECP and cased hole gravel pack well completion methods are 0.52 and 0.4799 respectively, which means slotted liner with ECP is a better option for this well completion. It is well known that SAGD is commonly applied in Christian Lake's oil-sands reservoirs, and the well completion method that SAGD used is slotted liner completion method, so this can demonstrate that the new proposed method is convenient and useful. However, because the weight is determined by a subjective method, so final result can be guided by decision makers' (users') preferred criteria assumption and weighting, so it is important for decision makers to give their preference based on real situation and companies' needs.

Chapter 7 Case study 2- Light oil production in He 50

This chapter utilizes data of a well in He 50, which is a fault block oil reservoir located in northeast part of Hezhuang oil field. The different part between case 1 and case 2 is the well in case 1 is a horizontal well with heavy oil, and the well in case 2 is a vertical well with light oil.

7.1 Reservoir failure mode identification

This section describes how to identify reservoir's failure mode by using the new proposed method.

7.1.1 Sanding

The data used to determine sanding is shown in Table 7.1, and their related weights are calculated in chapter 5.

Table 7. 1 Data used for sanding determination

Name of criterion	Quantitative value
Cementing agents	Calcareous cement
Type of cementation	Basal cementation
Porosity	21%
In-place fluid viscosity(cp)	4.06 cp
API	52
Water-sensitive minerals	Include some montmorillonite, illite, smectite or chlorite
Density of rock (g/cm^3)	2.2
Compressional wave slowness (μs/m)	350
Poisson ratio	0.28
Young's modulus (10^4 MPa)	1.4
Transverse interval transit time (μs/m)	*420*
FBHP (MPa)	10.535
Gravity of acceleration (m/s^2)	10
Reservoir pressure (MPa)	20.56
Depth of reservoir (m)	2093.8
Compressive strength of rock (MPa)	*30*

Then according to the judgement criteria mentioned in chapter 4, we can get quantitative values of each criterion, which is shown in Table 7.2.

Table 7. 2 Quantitative values of sanding judgement criteria

Name of criterion	Quantitative value
Cementing agent	0.7
Cementation	0.3
Porosity	0.7
Fluid viscosity	0.3
API	0.3
Water-sensitive minerals	0.7
Compose module method=49587.3	0
SLB method=4.15*10^7	0
Sanding index method=1.06*10^4	1
Compressive strength method=4.448	0

The absolute weight of each criterion is shown in Table 5.20, which can be adjusted based on oil companies' own situation. Then the final result can be calculated by multiplying quantitative values by absolute weight.

The final result is equal to 0.3270756, which is smaller than 0.5, so this well has very low probability of sanding. Therefore, there is no need to adopt sand control well completion method.

7.1.2 Wellbore stability

The data used to determine wellbore stability is shown in Table 7.3. Because Mohr-Coulomb criterion does not consider σ2, so some researchers think it is not accurate enough, therefore, the weight assignment is 0.4 for Mohr-Coulomb criterion and 0.6 for Drucker-Prager criterion.

Table 7. 3 Data used for wellbore stability determination

Name of criterion	Quantitative value
Minimum effective principal stresses, Mpa	48.6
Maximum effective principal stresses, Mpa	34.4
Cohesive strength, Mpa	2.13
Friction angle	20

Biot poroelastic constant	0.9
Pore pressure	20.56

Table 7. 4 Quantitative values of wellbore stability judgement criteria

Name of criterion	Quantitative value
Mohr-Coulomb criterion	0
Drucker-Prager criterion	0

The final result is equal to 0, which means this well is relatively stable, and the well completion method do not need to be equipped with the ability to support wellbore. And so far, all of the well completion methods are suitable for this well.

7.1.3 Water/ gas cut

This reservoir has very complicated oil-water relationship as there is a large area of active edge water nearby. Therefore, the possibility of water cut is very high, and only cased hole well completion method, slotted liner with ECP and cased hole gravel pack well completion methods can satisfy this requirement.

7.1.4 Stimulation

The data used to determine wellbore stability is shown in Table 7.5.

Table 7. 5 Data used for fracturing determination

Name of criterion	Quantitative value
Permeability($10^{-3}\mu m^2$)	18.5
Porosity	21%
Net pay thickness (m)	6.9
Recoverable reserves ($10^8 m^3$)	*0.0242*
Water saturation (%)	49
Flow coefficient ($10^{-3}\mu m^2 \cdot m/mPa\cdot s$)	425.5
Reservoirs pressure (MPa)	20.56
Petroleum production (t/d)	8.7

According to equation 4.14 and 4.15, the normalized value of each criterion can be calculated, and the result is shown in Table 7.6. The weight can also be determined by using fuzzy AHP method, and the result is shown in Table 7.7, and the final result is equal to 0.679, which means this well is suitable for fracturing, and those three well completion methods mentioned before are all suitable for fracturing.

Table 7. 6 Quantitative values of fracturing judgement criteria

Name of criterion	Quantitative value
Permeability($10^{-3}\mu m^2$)	0.9649
Porosity	0.6042
Net pay thickness (m)	0.6125
Recoverable reserves ($10^8 m^3$)	0.00284
Water saturation (%)	0.2
Flow coefficient ($10^{-3}\mu m^2 \cdot m/mPa \cdot s$)	0.6383
Reservoirs pressure (MPa)	0.6224
Petroleum production (t/d)	0.7345

Table 7. 7 Weighting values of fracturing judgement criteria

Name of criterion	Quantitative value
Permeability($10^{-3}\mu m^2$)	0.192
Porosity	0.192
Net pay thickness (m)	0.049
Recoverable reserves ($10^8 m^3$)	0.033
Water saturation (%)	0.049
Flow coefficient ($10^{-3}\mu m^2 \cdot m/mPa \cdot s$)	0.033
Reservoirs pressure (MPa)	0.136
Petroleum production (t/d)	0.318

7.2 Productivity, cost, and HSE indexes

7.2.1 Quantitative values of indexes

Evaluation matrix needs to be established first before determining final weight, which includes initial production, cumulative production, well completion cost, NPV, EPI, and risk index.

Table 7.8 shows the data required for calculating productivity and cost, and Table 7.9 shows the possible productivity of slotted liner with ECP and cased hole gravel pack well completion methods.

Table 7. 8 Data used for productivity and cost determination

Name of criterion	Quantitative value
Horizontal permeability, μm^2	0.004
Vertical permeability, μm^2	0.0185
Anisotropy coefficient	1.235
Borehole' s eccentric distance, m	0
Oil formation volume factor	1.195
Pay zone, m	6.9
Drainage radius, m	106
Fluid viscosity, mPa·s	4.06
Wellbore radius, m	0.183
Skin factor of CHGP	*1.87* [69]
Skin factor of slotted liner with ECP	*14.59* [115]
Skin factor of cased hole well completion method	*0.93* [69]

Table 7. 9 Quantitative values of productivity

	Initial production, m^3/d	cumulative production, m^3, t=90
CHGP	0.41	73.76
Slotted liner with ECP	0.15	27.28
Cased hole well completion	0.48	88.33

Then the evaluation conclusive table can be established and shown in Table 7.10.

Table 7. 10 Summative table of evaluation indexes

	Initial pro	Cumulative pro	Well Completion cost (￥)	NPV (Million ￥) T=3 years	EPI	Risk index
CHGP	0.41	73.76	*239066*	*2516.9*	9	0.69
SL(ECP)	0.15	27.28	*155005*	*1343.2*	5	0.65
Cased hole	0.48	88.33	*196500*	*3213.7*	8	0.47

Then the evaluation indexes matrix can be gotten and shown as follows.

$$A=\begin{bmatrix} 0.41 & 73.76 & 239066 & 2516.9 & 9 & 0.69 \\ 0.15 & 27.28 & 155005 & 1343.2 & 5 & 0.65 \\ 0.48 & 88.33 & 196500 & 3213.7 & 8 & 0.47 \end{bmatrix}$$

There are two kinds of indexes within this evaluation system, the first kind includes initial productivity, cumulative productivity and NPV, they are the bigger the better indexes. The second kind is called the smaller the better indexes, which includes well completion cost, EPI and risk index. Then based on equation 5.18 and 5,19, the next step is to apply dimensionless method on judgement matrix, and B is the matrix after normalized.

$$B=\begin{bmatrix} 0.788 & 0.761 & 0 & 0.627 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0.182 \\ 1 & 1 & 1.149 & 1 & 0.250 & 1 \end{bmatrix}$$

7.2.2 Weight determination

a. Fuzzy AHP method

Assume the preference grade of evaluation indexes in this case is Productivity > Cost >HSE

The fuzzy triangular complementary matrix $A = (a_{ij})_{n*n}$ for second level is shown in Table 7.11, and final result for second level is shown in Table 7.12.

Productivity is obviously more important than cost (0.7), cost is weakly more important than HSE (0.6+), and productivity is strongly more important than HSE (0.8-).

Table 7. 11 Fuzzy triangular complementary matrix for second level

	HSE			Cost			Productivity		
HSE	0.500	0.500	0.500	0.200	0.400	0.500	0.100	0.200	0.400
Cost	0.500	0.600	0.800	0.500	0.500	0.500	0.200	0.300	0.400
Productivity	0.600	0.800	0.900	0.600	0.700	0.800	0.500	0.500	0.500

Table 7. 12 Ranking for second level

HSE	Cost	Productivity
0.233	0.313	0.454

The triangular complementary matrix for lower level is shown in Table 7.13 and the final absolute weight for each criterion is shown in Table 7.14.

- Productivity: Cumulative productivity is strongly more important (0.8) than initial productivity.
- Cost: NPV is weakly more important (0.6+) than well completion cost.
- HSE: Risk index is obviously more important (0.7+) than EPI.

Table 7. 13 Fuzzy triangular complementary matrix for lower level

	Cumulative pro			Initial pro		
Cumulative pro	0.500	0.500	0.500	0.700	0.800	0.900
Initial pro	0.100	0.200	0.300	0.500	0.500	0.500

	Well completion cost			NPV		
Well completion cost	0.500	0.500	0.500	0.200	0.400	0.500
NPV	0.500	0.600	0.800	0.500	0.500	0.500

	Risk index			EPI		
Risk index	0.500	0.500	0.500	0.600	0.700	0.900
EPI	0.100	0.300	0.400	0.500	0.500	0.500

Table 7. 14 Absolute weights of criteria

Initial productivity	0.0952
Cumulative productivity	0.3583
Well completion cost	0.1215
NPV	0.1913
EPI	0.0683
Risk index	0.1651

b. Entropy method

Step 1: Form original index data matrix

$$A=\begin{bmatrix} 0.414 & 75.08 & 239066 & 2516.9 & 9 & 0.69 \\ 0.385 & 70.27 & 155005 & 1343.2 & 5 & 0.65 \\ 0.484 & 88.33 & 196500 & 3213.7 & 8 & 0.47 \end{bmatrix}$$

Step 2: Apply dimensionless method to the data matrix

$$B=\begin{bmatrix} 0.788 & 0.761 & 0 & 0.627 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0.182 \\ 1 & 1 & 1.149 & 1 & 0.250 & 1 \end{bmatrix}$$

Step 3: Calculate index's weight of each evaluation object

$$P=\begin{bmatrix} 0.441 & 0.432 & 0 & 0.385 & 0 & 0 \\ 0 & 0 & 0.465 & 0 & 0.8 & 0.154 \\ 0.559 & 0.568 & 0.535 & 0.722 & 0.2 & 0.846 \end{bmatrix}$$

Step 4: Determine entropy of each index

$$e = [0.625 \quad 0.622 \quad 0.631 \quad 0.549 \quad 0.455 \quad 0.391]$$

Step 5: Determine variation coefficient of each index

$$d = [0.375 \quad 0.378 \quad 0.369 \quad 0.451 \quad 0.545 \quad 0.609]$$

Step 6: Calculate entropy weight of each index

$$w = [0.138 \quad 0.139 \quad 0.135 \quad 0.165 \quad 0.199 \quad 0.223]$$

Therefore, the rank of weights determined by entropy method is risk index>EPI> NPV >cumulative productivity>initial productivity>well completion cost, which means the rank of grade determined by objective method is contradict with decision maker's wish, so the α here is equal to 0.

7.2.3 Well completion method determination

Based on absolute weights and evaluation indexes' matrix, the final points of slotted liner with ECP, cased hole with gravel pack, and cased hole well completion methods are 0.2704, 0.1366 and 0.6132 respectively, which means cased hole well completion method is a better option for this well. And according to reality, cased hole well completion method is applied in this well, and this well gets very good productivity after applying fracturing, so this case can also demonstrate that this well completion selection method is very useful and effective.

Chapter 8. Development of a well completion method optimal selection software

8.1 Software prototype development

As shown in chapter 6 and 7, this optimal selection model can be successfully applied in reality, so in order to let this model can assist field operation by providing guidance of well completion method selection, a well completion method optimal selection software is designed and realized based on C#.

This software has two parts, one is optimal selection for horizontal wells, and the other part is for vertical wells. This software starts from excluding some well completion methods by the need of reservoir failure mode supporting and stimulation requirement, and then the rest of methods will be pairwise compared from three perspectives to get the most suitable well completion method for a specific well. The logic of this software is shown in Figure 8.2.

8.2 User interfaces of software

Well completion method optimal selection software's user interface is introduced in this section. Figure 8.1 shows the start interface of this software, and there are two choices for users: vertical

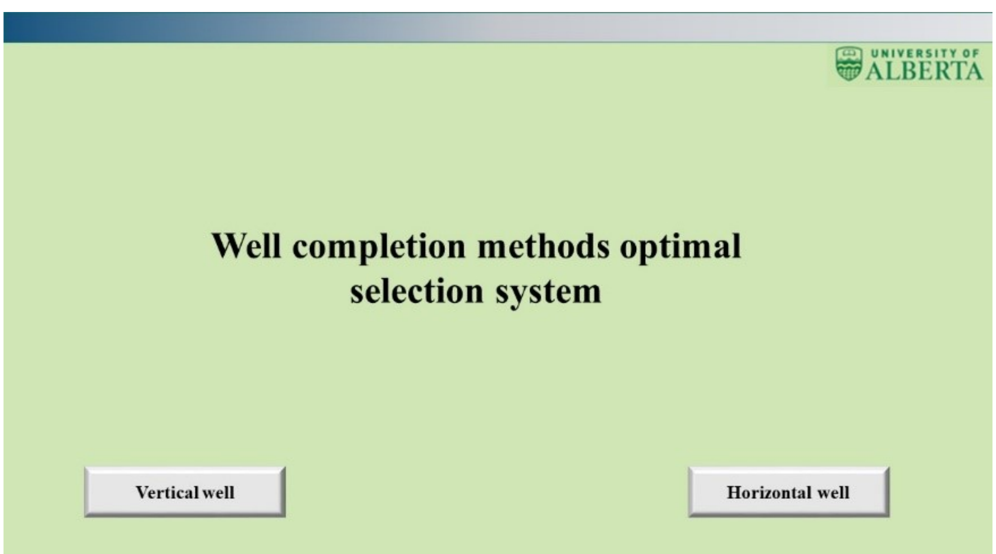


Figure 8. 1 The start UI of software

well or horizontal well. Then, as shown in Figure 8.3, there are five evaluation indexes, and users can click any of them to input relevant information.

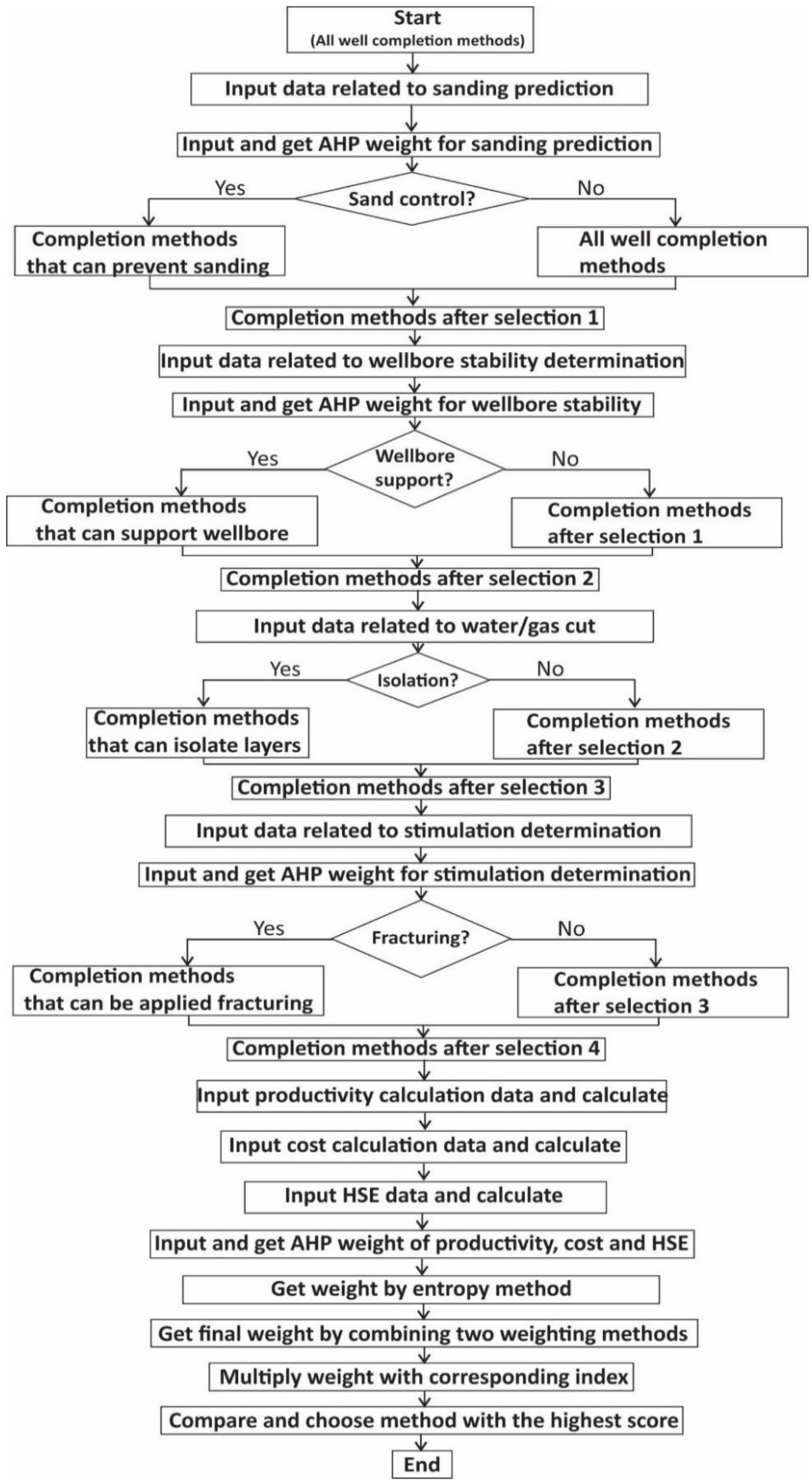


Figure 8. 2 Flow chart of software prototype

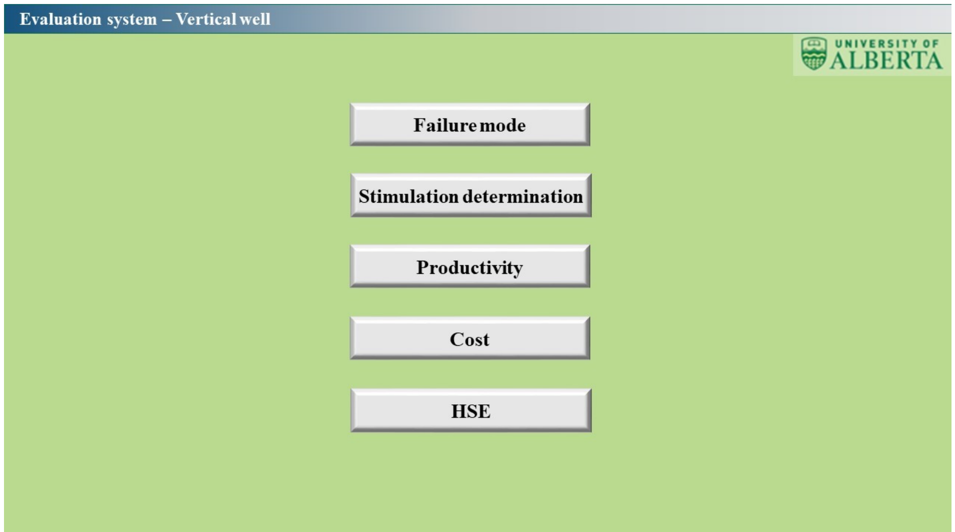


Figure 8. 3 UI of valuation indexes

The next step is to identify failure mode, like shown in Figure 8.4, users can input data related to sanding prediction, and the quantized data will be shown on the interface after clicking calculate button.

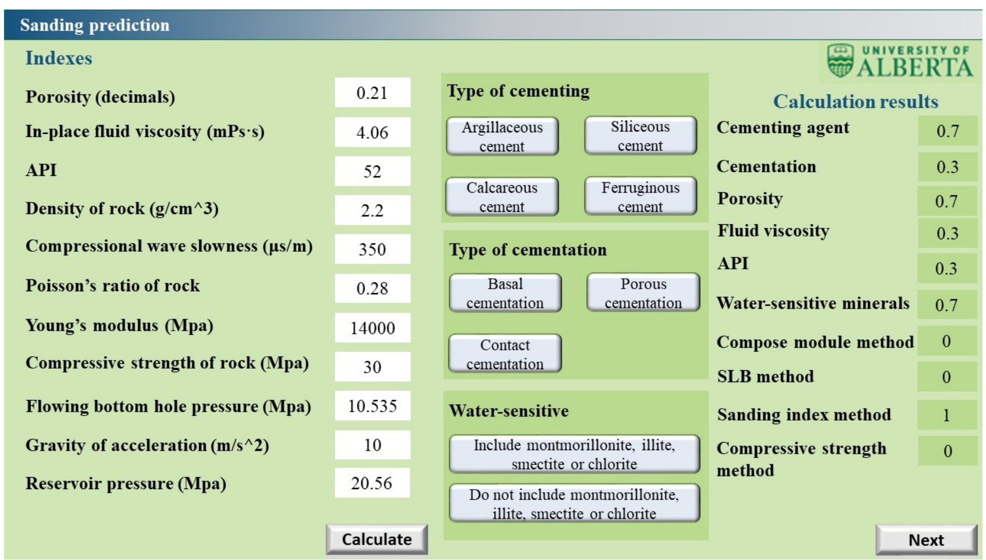


Figure 8. 4 UI of sanding judgement criteria's determination and quantization

Figure 8.5 to Figure 8.7 show the weight determination interface for sanding prediction. There are four tables in this weight determination system, and Figure 8.5 presents pairwise comparison for second level criteria, the weight will be calculated and shown on the interface after clicking calculate button. Figure 8.6 shows pairwise comparison for lower level criteria, and after inputting data for all four tables, users can click final button to get the final weights of every criterion, which is shown in Figure 8.7.

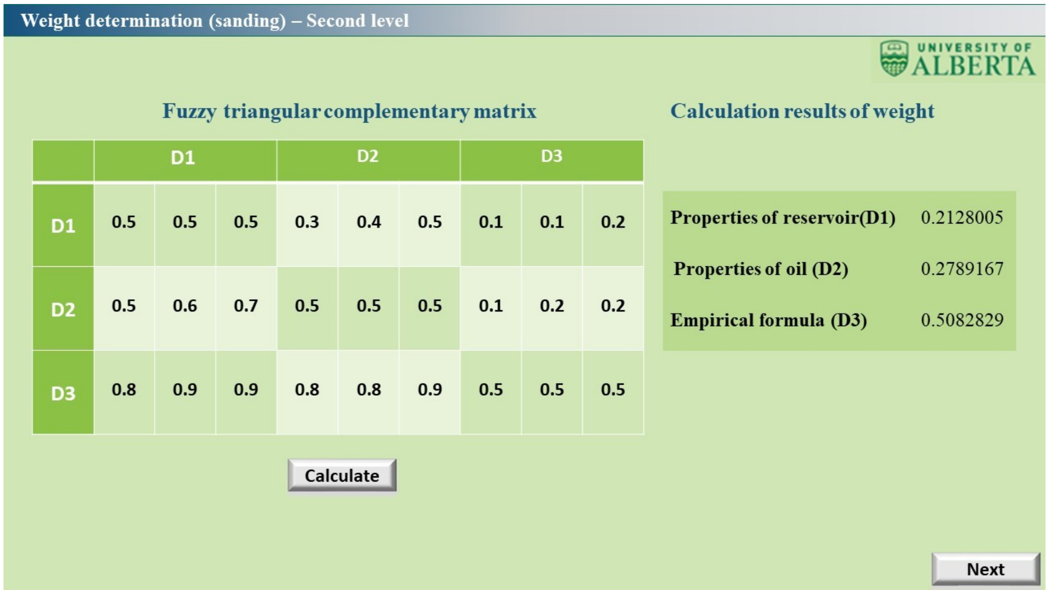


Figure 8. 5 UI of weight determination for sanding's second level criteria

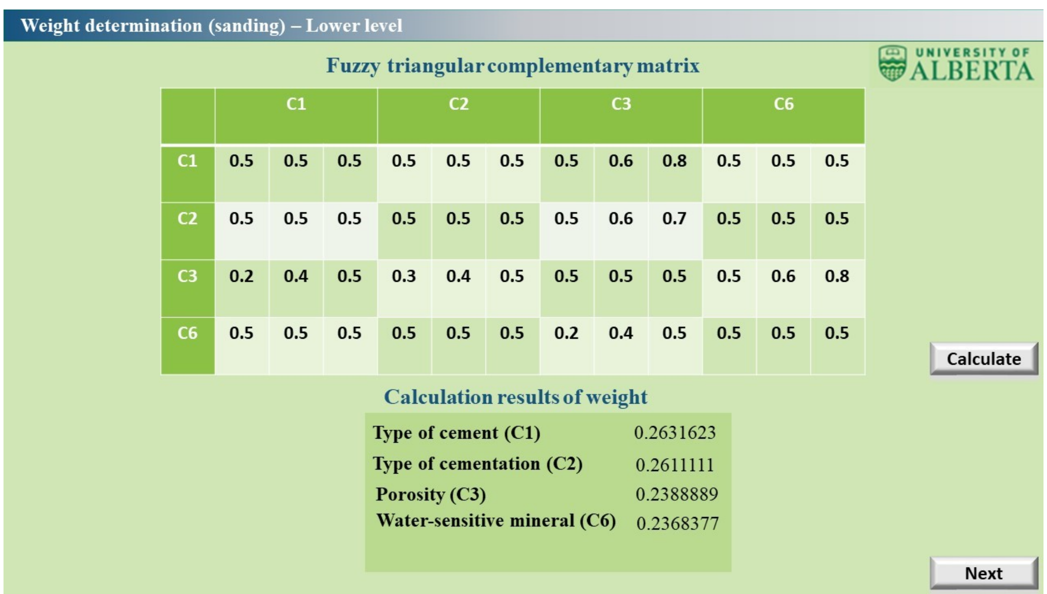


Figure 8. 6 UI of weight determination for sanding's lower level criteria

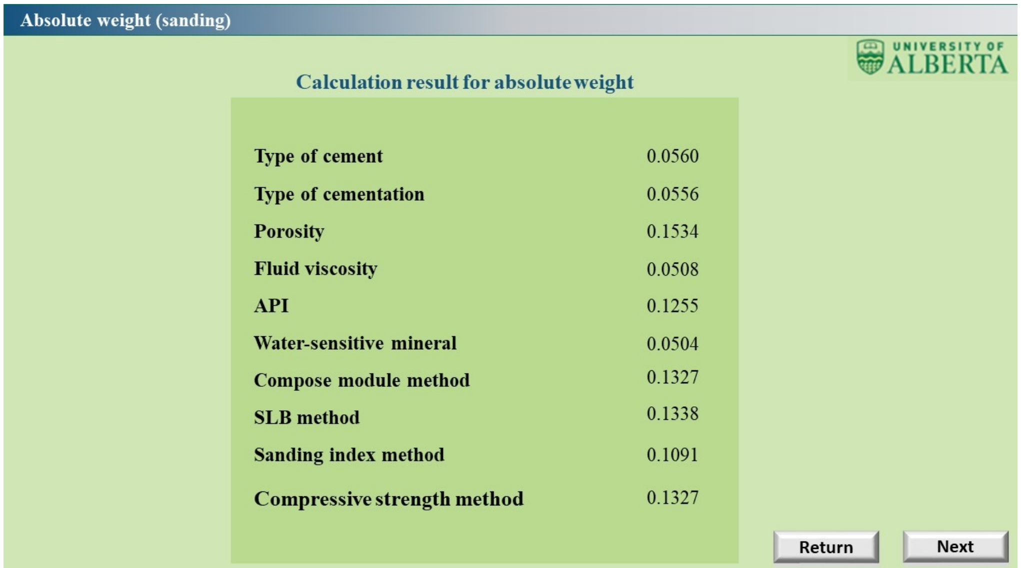


Figure 8. 7 UI of final weights for sanding judgement criteria

After determining weights of each criterion, the final conclusion can be got by mutiplying weights with correspoing quantified judgement criterion, and it is shown in Figure 8.8.

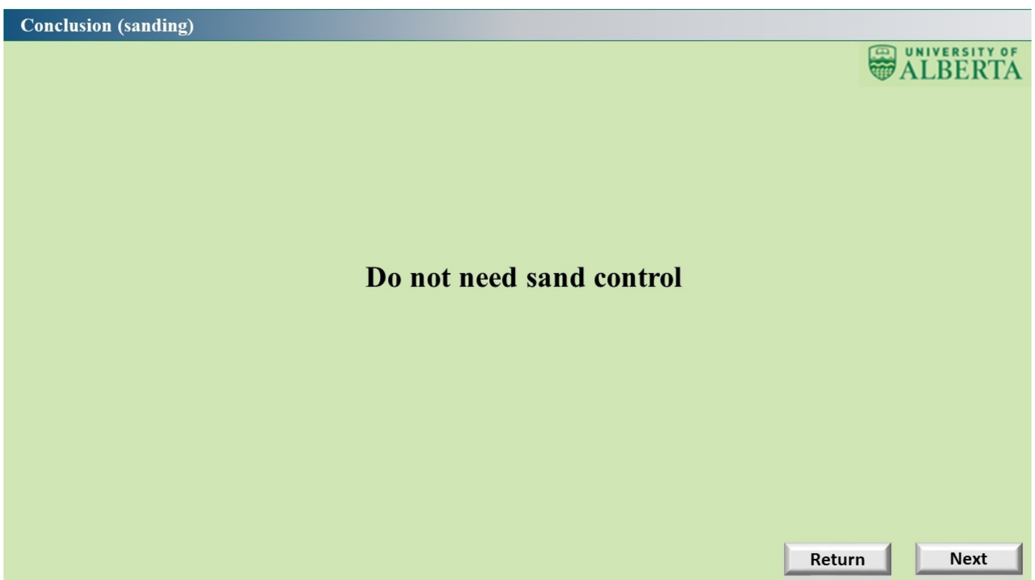


Figure 8. 8 UI of final result for sanding prediction

Besides sanding prediction, this software also can calculate other four evaluation systems and get corresponding quantified numbers that can lead to optimal selection of well completion methods, which is shown from Figure 8.9 to Figure 8.11.

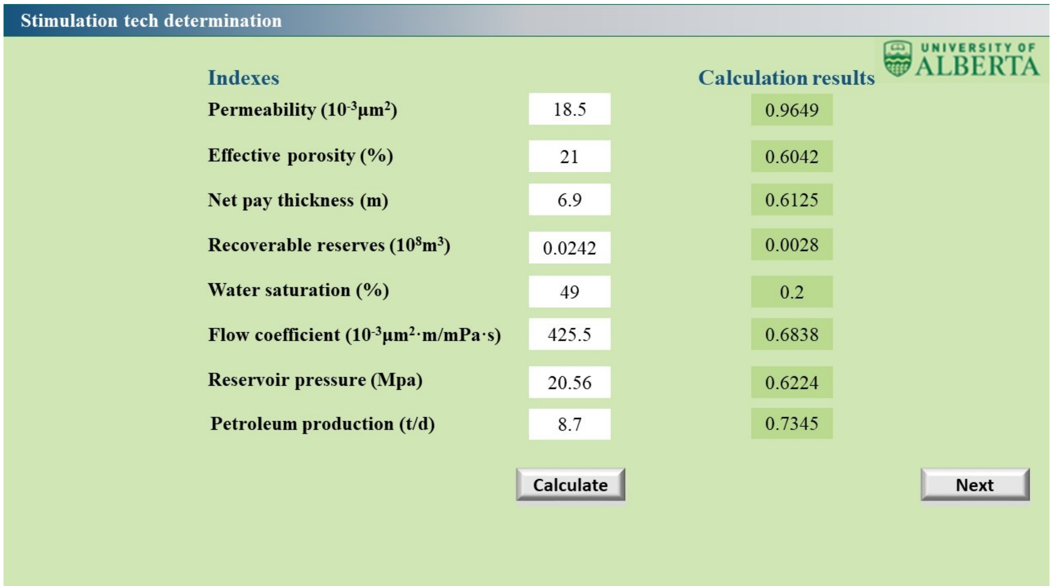


Figure 8. 9 UI of stimulation tech judgement criteria's determination and quantization

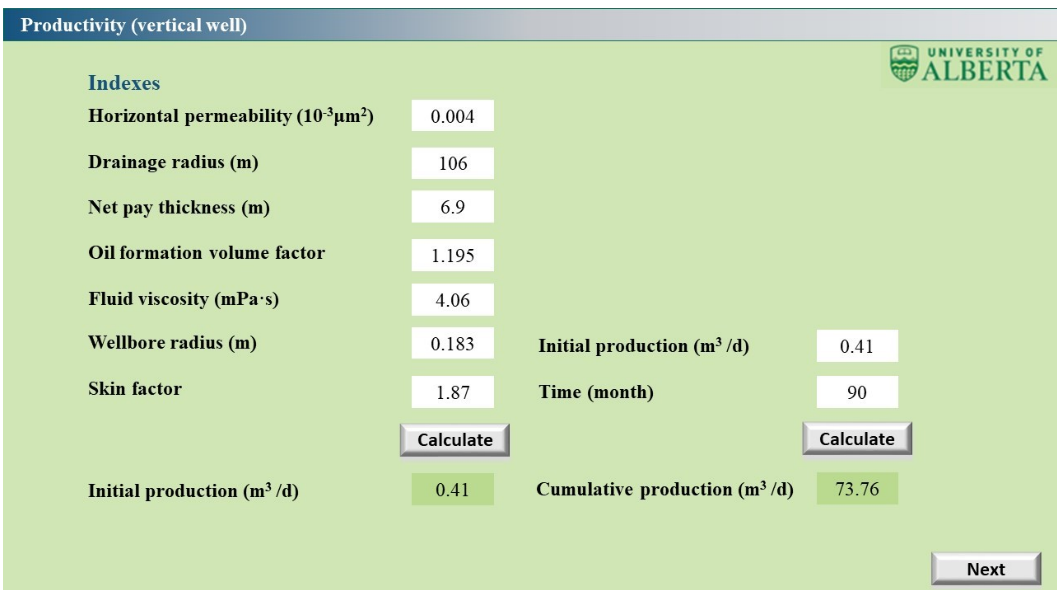


Figure 8. 10 UI of productivity's determination

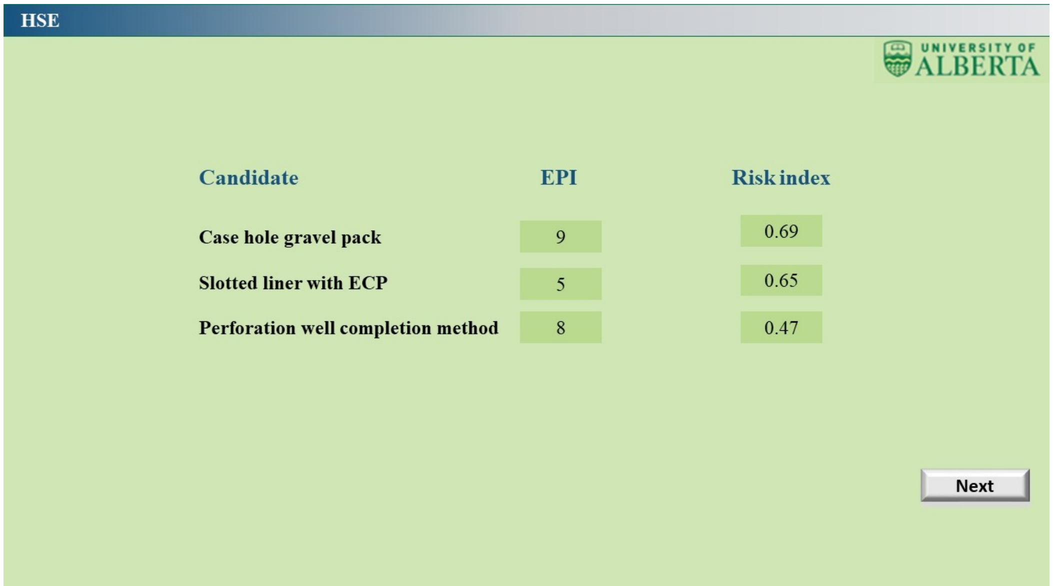


Figure 8. 11 UI of HSE determination

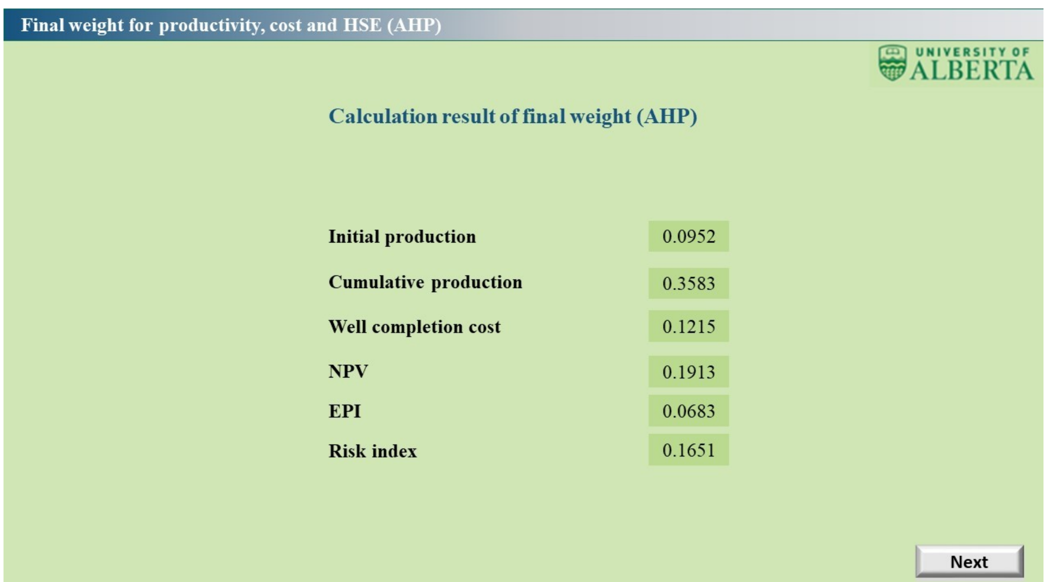


Figure 8. 12 UI of final weight for productivity, cost and HSE (AHP)

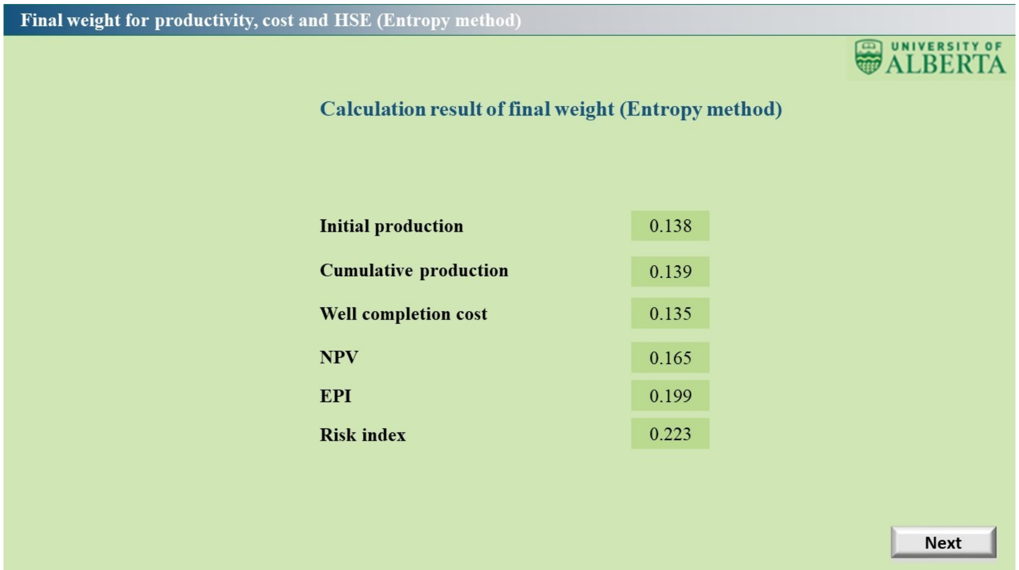


Figure 8. 13 UI of final weight for productivity, cost and HSE (Entropy method)

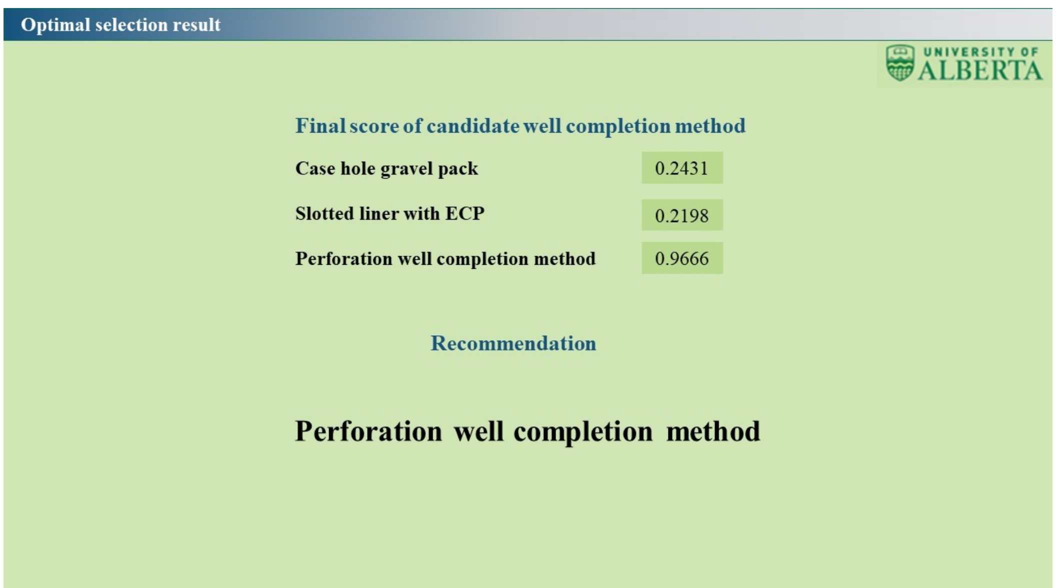


Figure 8. 14 Final result and recommendation

Chapter 9. Conclusions and future work

9.1 Conclusions

This thesis focuses on building a comprehensive system to select an optimum well completion method for different reservoirs, which makes the decision-making process more efficient and the final decision more reliable and justifiable.

Based on the research, some of the well completion selection models and methods only depend on experts' knowledge, experience and judgement, which are too subjective and cannot cover all the aspects needed to be considered during the selection. Others depend on numerical indexes, like initial production, operation cost etc., which ignore experts' important instructions and are overly simplified. In addition, almost all evaluation systems now are too general and only include cost criteria, production criteria, time criteria and risk criteria, which cannot evaluate well completion system comprehensively. To overcome this challenge existed in the existing selection methods, this thesis proposes a new feature-based selection system, which combines MADM, MODM, subjective method and objective method together. Characteristics of this newly proposed system is summarized as follow.

- Five primary evaluation modules are included: reservoir failure mode identification, stimulation technology determination, productivity, cost and HSE module. Each of these modules has its own corresponding second level criteria. Based on my research, there is no well completion selection system has ever considered HSE and stimulation technology demand before.
- Risk assessment is introduced in this system to improve safety and reliability of finial decisions, which can also save time of doing risk assessment independently.
- MADM and MODM are combined into one system, which can solve complex problems with multiple influence factors in a better way.
- There are a lot of uncertainties exist in this decision-making system, however, in previous studies, almost all inputs are crisp deterministic numbers when determining weights.

Therefore, this thesis performs fuzzy AHP to determine weights. This approach can better deal with problems under uncertain surrounding.

- A new pairwise comparison scale for AHP is established, which is more suitable for fuzzy AHP's judgement.
- The way to do AHP's consistency check is modified and improved.
- The selection system proposed by this thesis is very flexible. This system can meet different reservoirs' needs and companies' requirements based on their own conditions by adjusting weights, which can have extensive applicability
- Both subjective and objective MCDM methods have their own pros and cons, so the proposed system combines Fuzzy AHP and entropy method together to achieve complementation, which is more scientific and more accurate to get reasonable weights.
- Complete a well completion methods optimum selection software based on C#.

In addition, two cases are used to demonstrate the feasibility of this system, which includes vertical and horizontal wells, heavy oil reservoir and light oil reservoir. The outcomes show that this system can make the selection of well completion methods more efficient and reliable. It is beneficial for oil companies as this system can make corresponding changes according to decision makers' requirements and data accuracy.

9.2 Future Work

Based on the discoveries in this thesis, further studies can be conducted in the future.

- Integrate numerical reservoir simulation software into this system to improve the accuracy of evaluation modules.
- This selection system can be expanded, which can also be used to select appropriate well completion equipment.
- Evaluation modules can be expanded, like adding the need of acidizing for stimulation module, ROI for cost module etc.

- This thesis combines AHP and entropy method together, and there are many other MCDM methods can be utilized. Therefore, different combination should be tested to see whether they result different choices or not.

Bibliography

[1] J. Bellarby, *Well Completion Design*. Elsevier, 2009.

[2] R. Khosravanian and D. A. Wood, “Selection of high-rate gas well completion designs applying multi-criteria decision making and hierarchy methods,” *J. Nat. Gas Sci. Eng.*, vol. 34, pp. 1004–1016, Aug. 2016.

[3] S. D. Pohekar and M. Ramachandran, “Application of multi-criteria decision making to sustainable energy planning—A review,” *Renew. Sustain. Energy Rev.*, vol. 8, no. 4, pp. 365–381, Aug. 2004.

[4] S. D. Joshi, *Horizontal Well Technology*. PennWell Books, 1991.

[5] K. Godwin, B. Gadiyar, and H. Riordan, “Simultaneous Gravel Packing and Filter-Cake Cleanup With Shunt Tubes in Openhole Completions: A Case History From the Gulf of Mexico,” *SPE Drill. Complet.*, vol. 17, no. 03, pp. 174–178, Sep. 2002.

[6] L. G. Jones, R. J. Tibbles, L. Myers, D. Bryant, J. Hardin, and G. Hurst, “Gravel Packing Horizontal Wellbores with Leak-Off Using Shunts,” presented at the SPE Annual Technical Conference and Exhibition, 1997.

[7] J. M. Perdue, “Completion Experts Study Gulf of Mexico Horizontal Screen Failures,” *Pet. Eng. Int.*, vol. 69, no. 6, Jun. 1996.

[8] V. B. Jackson and T. R. Tips, “Case Study: First Intelligent Completion System Installed in the Gulf of Mexico,” presented at the Offshore Technology Conference, 2000.

[9] A. A. Ajayi, M. R. Konopczynski, and C. Giuliani, “Defining and Implementing Functional Requirements of an Intelligent-Well Completion System,” presented at the Latin American & Caribbean Petroleum Engineering Conference, 2007.

[10] C. D. Stair, E. R. Bruesewitz, J. B. Shivers, D. T. Rajasingam, and M. E. P. Dawson, “Na Kika Completions Overview: Challenges and Accomplishments,” presented at the Offshore Technology Conference, 2004.

[11] J. J. Brnak, B. Petrich, and M. R. Konopczynski, “Application of SmartWell Technology to the SACROC CO2 EOR Project: A Case Study,” presented at the SPE/DOE Symposium on Improved Oil Recovery, 2006.

[12] G. Zhang, J. Lu, and Y. Gao, *Multi-Level Decision Making: Models, Methods and Applications*. Springer, 2015.

[13] H. A. Simon *et al.*, “Decision Making and Problem Solving,” *Interfaces*, vol. 17, no. 5, pp. 11–31, Oct. 1987.

[14] T. Daim, T. Oliver, and J. Kim, *Research and Technology Management in the Electricity Industry: Methods, Tools and Case Studies*. Springer Science & Business Media, 2013.

[15] J. Xu and Z. Tao, *Rough Multiple Objective Decision Making*. CRC Press, 2011.

[16] J. Climaco, *Multicriteria Analysis: Proceedings of the XIth International Conference on MCDM, 1–6 August 1994, Coimbra, Portugal*. Springer Science & Business Media, 2012.

[17] A. Guerraggio, E. Molho, and A. Zaffaroni, "On the notion of proper efficiency in vector optimization," *J. Optim. Theory Appl.*, vol. 82, no. 1, pp. 1–21, Jul. 1994.

[18] A. Charnes and W. W. Cooper, "Goal programming and multiple objective optimizations: Part 1," *Eur. J. Oper. Res.*, vol. 1, no. 1, pp. 39–54, Jan. 1977.

[19] M. M. Köksalan, J. Wallenius, and S. Zionts, *Multiple Criteria Decision Making: From Early History to the 21st Century*. World Scientific, 2011.

[20] X. Gandibleux, *Multiple Criteria Optimization: State of the Art Annotated Bibliographic Surveys*. Springer Science & Business Media, 2006.

[21] C. Diakaki, E. Grigoroudis, N. Kabelis, D. Kolokotsa, K. Kalaitzakis, and G. Stavrakakis, "A multi-objective decision model for the improvement of energy efficiency in buildings," *Energy*, vol. 35, no. 12, pp. 5483–5496, Dec. 2010.

[22] F. Schramm and D. C. Morais, "Decision support model for selecting and evaluating suppliers in the construction industry," *Pesqui. Oper.*, vol. 32, no. 3, pp. 643–662, Dec. 2012.

[23] N. H. Zardari, K. Ahmed, S. M. Shirazi, and Z. B. Yusop, *Weighting Methods and their Effects on Multi-Criteria Decision Making Model Outcomes in Water Resources Management*. Cham: Springer International Publishing, 2015.

[24] P. J. Agrell, "A multicriteria framework for inventory control," *Int. J. Prod. Econ.*, vol. 41, no. 1, pp. 59–70, Oct. 1995.

[25] K. P. Yoon and C.-L. Hwang, *Multiple Attribute Decision Making: An Introduction*. SAGE Publications, 1995.

[26] K. Yoon, "A Reconciliation among Discrete Compromise Solutions," *J. Oper. Res. Soc.*, vol. 38, no. 3, pp. 277–286, 1987.

[27] C.-L. Hwang, Y.-J. Lai, and T.-Y. Liu, "A new approach for multiple objective decision making," *Comput. Oper. Res.*, vol. 20, no. 8, pp. 889–899, Oct. 1993.

[28] A. Assari, T. M. Mahesh, and E. Assari, "Role of Public Participation in Sustainability of Historical City: Usage of TOPSIS Method," *Indian J. Sci. Technol.*, vol. 5, no. 3, pp. 2289–2294, Mar. 2012.

[29] H. S. Byun and K. H. Lee, "A decision support system for the selection of a rapid prototyping process using the modified TOPSIS method," *Int. J. Adv. Manuf. Technol.*, vol. 26, no. 11–12, pp. 1338–1347, Nov. 2005.

[30] H.-S. Shih, H.-J. Shyur, and E. S. Lee, "An extension of TOPSIS for group decision making," *Math. Comput. Model.*, vol. 45, no. 7, pp. 801–813, Apr. 2007.

[31] M. Sevkli, "An application of the fuzzy ELECTRE method for supplier selection," *Int. J. Prod. Res.*, vol. 48, no. 12, pp. 3393–3405, Jun. 2010.

[32] E. Bekiaris and Y. J. Nakanishi, *Economic Impacts of Intelligent Transportation Systems: Innovations and Case Studies*. Elsevier, 2004.

[33] K. Govindan and M. B. Jepsen, "ELECTRE: A comprehensive literature review on methodologies and applications," *Eur. J. Oper. Res.*, vol. 250, no. 1, pp. 1–29, Apr. 2016.

[34] B. Roy, "The Outranking Approach and the Foundations of Electre Methods," in *Readings in Multiple Criteria Decision Aid*, Springer, Berlin, Heidelberg, 1990, pp. 155–183.

[35] J. Figueira, V. Mousseau, and B. Roy, "Electre Methods," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, Springer, New York, NY, 2005, pp. 133–153.

[36] J. Buchanan and P. Sheppard, *Ranking Projects Using the ELECTRE Method*.

[37] M. G. Rogers, M. Bruen, and L.-Y. Maystre, *Electre and Decision Support: Methods and Applications in Engineering and Infrastructure Investment*. Springer Science & Business Media, 2013.

[38] J. R. Figueira, S. Greco, and B. Roy, "ELECTRE methods with interaction between criteria: An extension of the concordance index," *Eur. J. Oper. Res.*, vol. 199, no. 2, pp. 478–495, Dec. 2009.

[39] H. Liao and Z. Xu, *Hesitant Fuzzy Decision Making Methodologies and Applications*. Springer, 2016.

[40] "Overview and Selection of Multicriteria Evaluation Methods for Mitigation-Adaptation Policy Instruments | Sensitivity Analysis | Climate Change Mitigation," *Scribd*. [Online]. Available: https://www.scribd.com/document/251252646/Overview-and-Selection-of-Multicriteria-Evaluation-Methods-for-Mitigation-Adaptation-Policy-Instruments. [Accessed: 17-Nov-2017].

[41] M. E. Amine, J. Pailhes, and N. Perry, "Critical Review of Multi-criteria Decision Aid Methods in Conceptual Design Phases: Application to the Development of a Solar Collector Structure," *Procedia CIRP*, vol. 21, pp. 497–502, Jan. 2014.

[42] A. Charnes and W. W. Cooper, “Management Models and Industrial Applications of Linear Programming,” *Manage Sci*, vol. 4, no. 1, pp. 38–91, Oct. 1957.

[43] S. M. Lee, *Goal programming methods for multiple objective integer programs*. Operations Research Division, American Institute of Industrial Engineers, 1979.

[44] C. E. SHANNON, “A mathematical theory of communication, Part I, Part II,” *Bell Syst Tech J*, vol. 27, pp. 623–656, 1948.

[45] Z. Zou, Y. Yun, and J. Sun, “Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment,” *J. Environ. Sci.*, vol. 18, no. 5, pp. 1020–1023, Sep. 2006.

[46] V. Singh, “249. The Entropy Theory as Tool for Modeling and Decision Making in Environmental and Water Resources,” *Water SA*, vol. 26, Jan. 2000.

[47] D. Diakoulaki, G. Mavrotas, and L. Papayannakis, “Determining objective weights in multiple criteria problems: The critic method,” *Comput. Oper. Res.*, vol. 22, no. 7, pp. 763–770, Aug. 1995.

[48] B. Srdjevic, Y. D. P. Medeiros, and A. S. Faria, “An Objective Multi-Criteria Evaluation of Water Management Scenarios,” *Water Resour. Manag.*, vol. 18, no. 1, pp. 35–54, Feb. 2004.

[49] J. S Dodgson, M. Spackman, P. AD, and L. Phillips, “Multi-Criteria Analysis: A Manual,” Jan. 2009.

[50] M. Oliveira, D. Fontes, and T. Pereira, “Multicriteria Decision Making: A Case Study in the Automobile Industry,” *Ann. Manag. Sci.*, vol. 3, pp. 109–128, May 2014.

[51] P. Sushil and M. Narayana, “Towards designing an expert system structure for inspection policy: An application of Analytic Hierarchy Process,” *SCIMA*, vol. 20, pp. 77–106, Jan. 1991.

[52] *The Analytic Hierarchy Process - Applications and Studies | Bruce L. Golden | Springer*.

[53] T. L. Saaty, “How to make a decision: The analytic hierarchy process,” *Eur. J. Oper. Res.*, vol. 48, no. 1, pp. 9–26, Sep. 1990.

[54] N. Subramanian and R. Ramanathan, “A review of applications of Analytic Hierarchy Process in operations management,” *Int. J. Prod. Econ.*, vol. 138, no. 2, pp. 215–241, Aug. 2012.

[55] M. Majumder, *Application of Geographical Information Systems and Soft Computation Techniques in Water and Water Based Renewable Energy Problems*. Springer, 2017.

[56] S. Zahir, “Synthesizing intensities of group preferences in public policy decisions using the AHP: Is it time for the ‘new democracy’?,” *Rev. Can. Sci. Adm. Montr.*, vol. 16, no. 4, pp. 353–366, Dec. 1999.

[57] S. H. Zanakis, A. Solomon, N. Wishart, and S. Dublish, “Multi-attribute decision making: A simulation comparison of select methods,” *Eur. J. Oper. Res.*, vol. 107, no. 3, pp. 507–529, Jun. 1998.

[58] C.-L. Hwang and K. Yoon, *Multiple Attribute Decision Making: Methods and Applications A State-of-the-Art Survey*. Springer Science & Business Media, 2012.

[59] L. Turcksin, A. Bernardini, and C. Macharis, “A combined AHP-PROMETHEE approach for selecting the most appropriate policy scenario to stimulate a clean vehicle fleet,” *Procedia - Soc. Behav. Sci.*, vol. 20, pp. 954–965, Jan. 2011.

[60] M. Behzadian, R. B. Kazemzadeh, A. Albadvi, and M. Aghdasi, “PROMETHEE: A comprehensive literature review on methodologies and applications,” *Eur. J. Oper. Res.*, vol. 200, no. 1, pp. 198–215, Jan. 2010.

[61] W. De Keyser and P. Peeters, “A note on the use of PROMETHEE multicriteria methods,” *Eur. J. Oper. Res.*, vol. 89, no. 3, pp. 457–461, Mar. 1996.

[62] M. Pirlot, “A Common Framework for Describing Some Outranking Methods,” *J. Multi-Criteria Decis. Anal.*, vol. 6, no. 2, pp. 86–92, Mar. 1997.

[63] J. L. Deng, “Introduction to Grey System Theory,” *J Grey Syst*, vol. 1, no. 1, pp. 1–24, Nov. 1989.

[64] J. W. K. Chan and T. K. L. Tong, “Multi-criteria material selections and end-of-life product strategy: Grey relational analysis approach,” *Mater. Des.*, vol. 28, no. 5, pp. 1539–1546, Jan. 2007.

[65] Y. Kuo, T. Yang, and G.-W. Huang, “The use of grey relational analysis in solving multiple attribute decision-making problems,” *Comput. Ind. Eng.*, vol. 55, no. 1, pp. 80–93, Aug. 2008.

[66] J. Johnston, C. Condie, T. Popescu, S. AI-Baker, and A. Rajvanshi, “A Multi-disciplinary Approach to Developing a Highly Faulted, Densely Fractured, Low Permeability Carbonate Reservoir, Offshore Qatar,” presented at the 19th World Petroleum Congress, 2008.

[67] J. Jia, L. Cao, S. Sang, T. Yi, and X. Zhou, “A case study on the effective stimulation techniques practiced in the superposed gas reservoirs of coal-bearing series with multiple thin coal seams in Guizhou, China,” *J. Pet. Sci. Eng.*, vol. 146, no. Supplement C, pp. 489–504, Oct. 2016.

[68] E. J. Idiodemise and A. Dosunmu, “A Model for Completion Selection for Multilateral and Multibranched Wells,” presented at the Nigeria Annual International Conference and Exhibition, 2007.

[69] L.-B. Ouyang, W. S. B. Huang, and R. C. Dickerson, "Efficient Cost Saving Through an Appropriate Completion Design," presented at the SPE Western Regional/AAPG Pacific Section/GSA Cordilleran Section Joint Meeting, 2006.

[70] S. Sinha, M. Yan, and Y. Jalali, "Completion Architecture: A Methodology for Integrated Well Planning," presented at the SPE/IADC Middle East Drilling Technology Conference and Exhibition, 2003.

[71] A. A. Garrouch, H. M. S. Lababidi, and A. S. Ebrahim, "An integrated approach for the planning and completion of horizontal and multilateral wells," *J. Pet. Sci. Eng.*, vol. 44, no. 3, pp. 283–301, Nov. 2004.

[72] C. K. Morooka and G. T. Castro, "A Methodology for the Selection of an Alternative for a Floating Production System," pp. 579–586, Jan. 2002.

[73] A. Rehman, N. Soponsakulkaew, O. O. Bello, and G. Falcone, "A Generic Model for Optimizing the Selection of Artifical Lift Methods for Liquid Loaded Gas Wells," presented at the SPE Annual Technical Conference and Exhibition, 2011.

[74] G. Yang and Z. Wang, "Adaptability Evaluation of Coal-bed MethaneWell Completion Methods Based on Multi-objective Decision-making Method," *SL Struct. Longev.*, vol. 9, no. 3, pp. 153–168, Mar. 2013.

[75] E. Ataallahi and S. R. Shadizadeh, "Fuzzy consequence modeling of blowouts in Iranian drilling operations; HSE consideration," *Saf. Sci.*, vol. 77, pp. 152–159, Aug. 2015.

[76] B. Mehrgini, H. Memarian, A. Fotouhi, and M. Moghanian, "Recognising the Effective Parameters and their Influence on Candidate-Well Selection for Hydraulic Fracturing Treatment by Decision Making Method," presented at the International Petroleum Technology Conference, 2014.

[77] S. Keivanpour, H. Haleh, and H. S. Ganjavi, "A Decision Model for Selecting the Optimum Oil Production Profile Using Multi Criteria Decision Making and Social Choice Theory," p. V014T08A008, Nov. 2014.

[78] B. Srdjevic, "Linking analytic hierarchy process and social choice methods to support group decision-making in water management," *Decis. Support Syst.*, vol. 42, no. 4, pp. 2261–2273, Jan. 2007.

[79] P. Pourafshary *et al.*, "Priority Assessment of Investment in Development of Nanotechnology in Upstream Petroleum Industry," presented at the SPE Saudi Arabia Section Technical Symposium, 2009.

[80] Fu, Li, et al., "Selection of CBM drilling & completion methods by hierarchical analysis," *Oil Drill. Prod. Technol. Shiyou Zuancai Gongyi*, vol. 33, no. 4, pp. 10–14, 2011.

[81] W. Renpu, “Advanced well completion engineering,” *CERN Document Server*, 2011. [Online]. Available: http://cds.cern.ch.login.ezproxy.library.ualberta.ca/record/1613552. [Accessed: 20-Nov-2017].

[82] T. G. Byrom, *Casing and Liners for Drilling and Completion: Design and Application*. Elsevier, 2014.

[83] W. L. Penberthy and C. M. Shaughnessy, *Sand control*. Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers, 1992.

[84] A. Filippov, R. Mack, L. Cook, P. York, L. Ring, and T. McCoy, “Expandable Tubular Solutions,” presented at the SPE Annual Technical Conference and Exhibition, 1999.

[85] K. DUPAL, “Well Design With Expandable Tubulars Reduces Costs and Increases Success in Deepwater Applications,” *Deep Offshore Technol. 2000*, 2000.

[86] Y. Ma, *Semantic Modeling and Interoperability in Product and Process Engineering: A Technology for Engineering Informatics*. Springer Publishing Company, Incorporated, 2013.

[87] E. M. Sanfilippo and S. Borgo, “What are features? An ontology-based review of the literature,” *Comput.-Aided Des.*, vol. 80, pp. 9–18, Nov. 2016.

[88] J. J. Shah, “Assessment of features technology,” *Comput.-Aided Des.*, vol. 23, no. 5, pp. 331–343, Jun. 1991.

[89] J. J. Shah and M. Mantyla, *Parametric and Feature Based CAD/Cam: Concepts, Techniques, and Applications*, 1st ed. New York, NY, USA: John Wiley & Sons, Inc., 1995.

[90] G. Brunetti, “Feature-Based Virtual Engineering,” in *Feature Based Product Life-Cycle Modelling*, Springer, Boston, MA, 2003, pp. 19–39.

[91] P. Di Stefano, F. Bianconi, and L. Di Angelo, “An approach for feature semantics recognition in geometric models,” *Comput.-Aided Des.*, vol. 36, no. 10, pp. 993–1009, Sep. 2004.

[92] N. Sajadfar, Y. Xie, H. Liu, and Y.-S. Ma, “A Review of Data Representation of Product and Process Models,” in *Semantic Modeling and Interoperability in Product and Process Engineering*, Springer, London, 2013, pp. 31–51.

[93] Y.-S. Ma and T. Tong, “Associative feature modeling for concurrent engineering integration,” *Comput. Ind.*, vol. 51, no. 1, pp. 51–71, May 2003.

[94] Y.-S. Ma, G. A. Britton, S. B. Tor, and L. Y. Jin, “Associative assembly design features: concept, implementation and application,” *Int. J. Adv. Manuf. Technol.*, vol. 32, no. 5–6, pp. 434–444, Mar. 2007.

[95] D. Du, “Study on 0.1∼0.9 scale in AHP | Request PDF.” [Online]. Available: https://www.researchgate.net/publication/293418035_Study_on_0109_scale_in_AHP. [Accessed: 31-Jan-2018].

[96] M. Batuhan Ayhan, “A Fuzzy AHP Approach for Supplier Selection Problem: A Case Study in a Gear Motor Company,” *ArXiv E-Prints*, vol. 1311, p. arXiv:1311.2886, Oct. 2013.

[97] Z. Xu, *Uncertain Multi-Attribute Decision Making: Methods and Applications*. Springer, 2015.

[98] R. Kong, *Power and Energy: Proceedings of the International Conference on Power and Energy (CPE 2014), Shanghai, China, 29-30 November 2014*. CRC Press, 2015.

[99] G.-F. Fuh, I. Ramshaw, K. C. Freedman, N. A. Abdelmalek, and N. Morita, “Use of Reservoir Formation Failure and Sanding Prediction Analysis for Viable Well-Construction and Completion-Design Options,” presented at the SPE Annual Technical Conference and Exhibition, 2006.

[100] K. Qiu *et al.*, “Practical Approach to Achieve Accuracy in Sanding Prediction,” presented at the SPE Asia Pacific Oil & Gas Conference and Exhibition, 2006.

[101] H. X, H. S, and J. F, *Physics of Petroleum Reservoirs*. Springer Berlin Heidelberg, 2017.

[102] W. Zeng and M. Zhang, “USING WEIGHTED METHOD TO JUDGE SAND PRODUCTION OF FORMATIONS AND SELECT WELL COMPLETION METHOD--《Natural Gas Industry》2006-05.” [Online]. Available: http://en.cnki.com.cn.login.ezproxy.library.ualberta.ca/Article_en/CJFDTOTAL-TRQG200605033.htm.

[103] W. Zou, “Predict Discussion on the Sand Production of Oil Well--《China Well and Rock Salt》2012-03.” [Online]. Available: http://en.cnki.com.cn.login.ezproxy.library.ualberta.ca/Article_en/CJFDTotal-ZJKY201203009.htm. [Accessed: 25-Jan-2018].

[104] X. Chen, C. P. Tan, and C. M. Haberfield, “Wellbore Stability Analysis Guidelines For Practical Well Design,” presented at the SPE Asia Pacific Oil and Gas Conference, 1996.

[105] A. A. Garrouch and A. S. Ebrahim, “Assessment of the Stability of Inclined Wells,” presented at the SPE Western Regional Meeting, 2001.

[106] L. R. Alejano and A. Bobet, “Drucker–Prager Criterion,” *Rock Mech. Rock Eng.*, vol. 45, no. 6, pp. 995–999, Nov. 2012.

[107] J. Rückheim, G. Voigtlaender, and M. Stein-Khokhlov, “The Technical and Economic Challenge of ‘Mature Gas Fields’: The Giant Altmark Field, a German Example,” presented at the SPE Europec/EAGE Annual Conference, 2005.

[108] Y. Xiong and Y. Pan, “Study on productivity prediction of the horizontal wells with completion methods of perforation series--《JOURNAL OF SOUTHWEST--CHINA PETROLEUM INSTITUTE》1996-02.” [Online]. Available: http://en.cnki.com.cn.login.ezproxy.library.ualberta.ca/Article_en/CJFDTOTAL-XNSY602.008.htm.

[109] S. A. Elgaghah, S. O. Osisanya, and D. Tiab, “A Simple Productivity Equation for Horizontal Wells Based on Drainage Area Concept,” presented at the SPE Western Regional Meeting, 1996.

[110] 邓晗, 李雪琴, 史赞绒, and 刘萍, “水平井完井方式优选及软件应用,” 中国石油和化工, no. 6, pp. 52–54, 2014.

[111] A. K. l Shyama and M. Pal, “TRIANGULAR FUZZY MATRICES,” *Iran. J. Fuzzy Syst.*, vol. 4, no. 1, pp. 75–87, Apr. 2007.

[112] S. C. Gupta and S. D. Gittins, “Christina Lake Solvent Aided Process Pilot,” presented at the Canadian International Petroleum Conference, 2005.

[113] M. B. Dusseault, “Comparing Venezuelan and Canadian Heavy Oil and Tar Sands,” presented at the Canadian International Petroleum Conference, 2001.

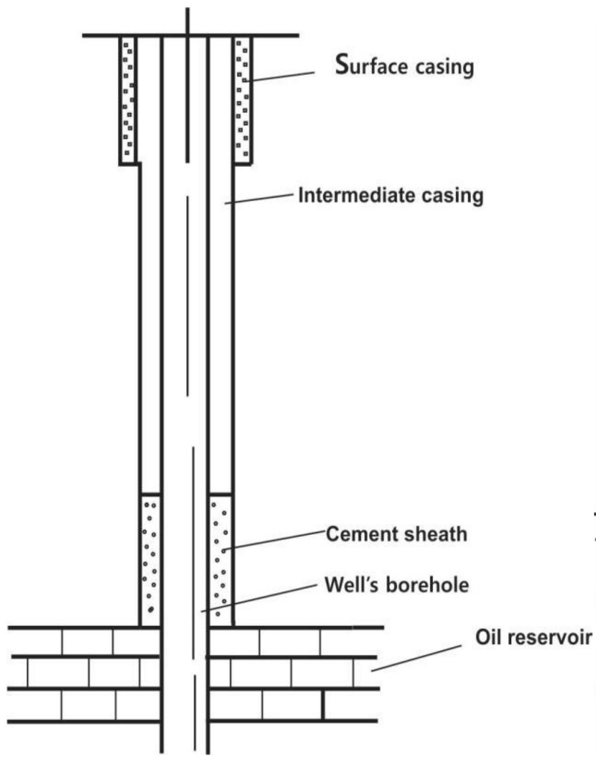
[114] A. M. Suranto and P. S. Heru, “Investigation of Multilevel Injector for Ramp-up Process in Vertical Well Using Steam Assisted Gravity Drainage Method,” *Energy Procedia*, vol. 105, pp. 4513–4518, May 2017.

[115] X. Wu, W. Xiao, X. Liu, G. Han, and Y. An, “Well Completion System Appraisal and Decision in Oil and Gas Reservoirs,” *Pet. Sci. Technol.*, vol. 29, no. 24, pp. 2592–2600, Oct. 2011.

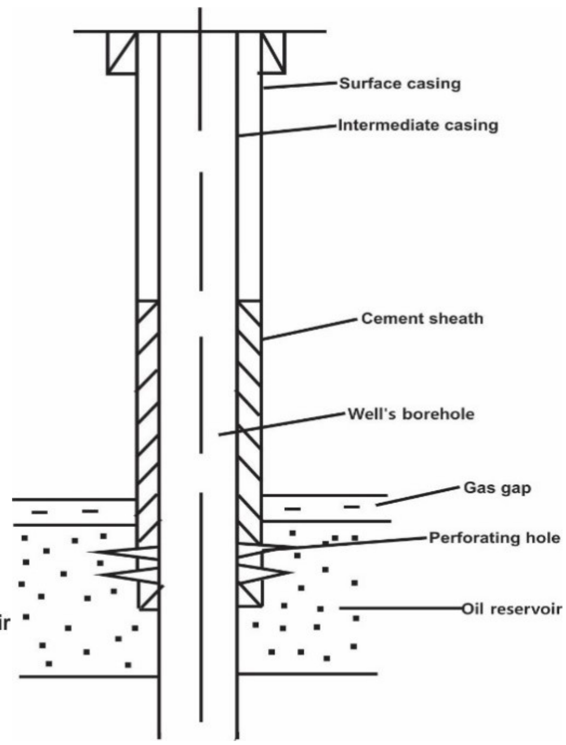
Appendices

Appendix A Figures of well completion methods

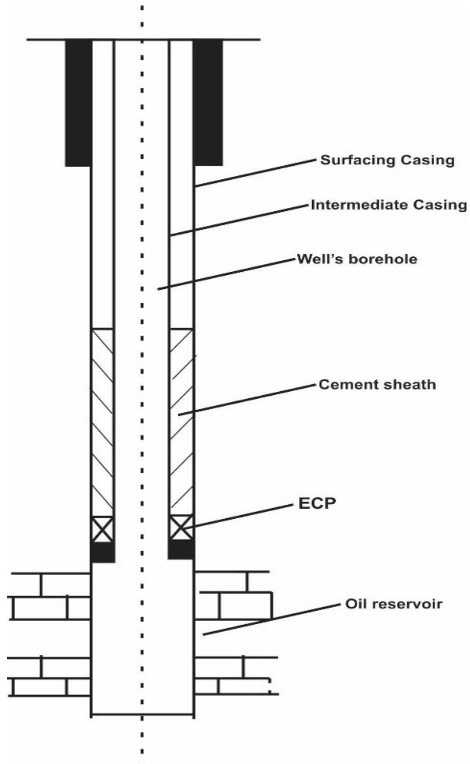
This section shows pictures of different kinds of well completion method.



(a) Initial open hole completion

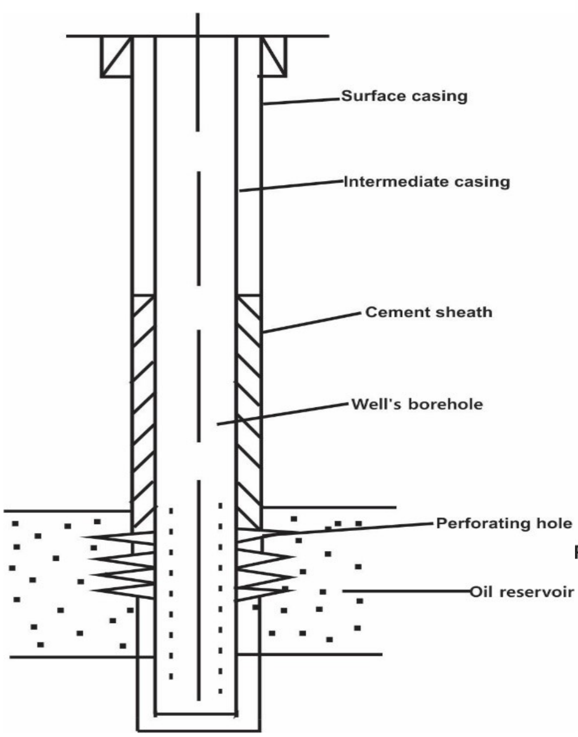


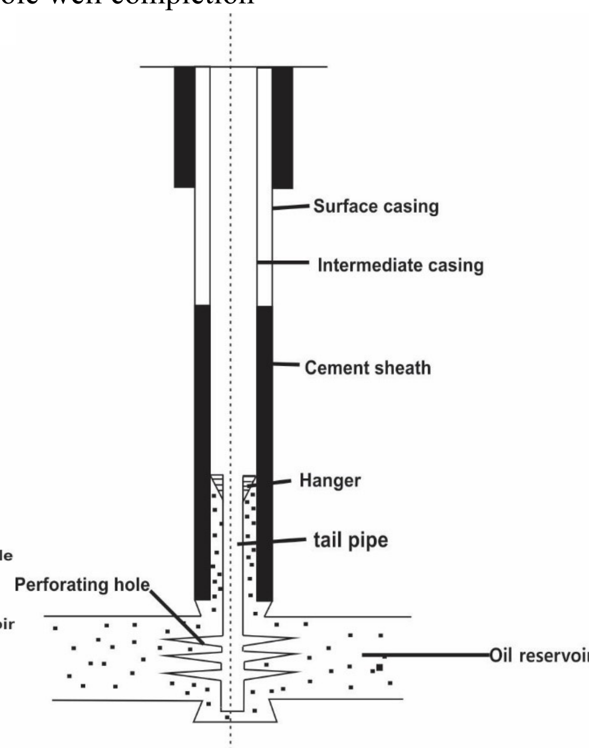
(b) Compound open hole completion



(c) Final open hole completion

Figure A1. 1 Open hole well completion





(a) Perforated casing completion (b) perforated tailpipe completion

Figure A1. 2 Cased hole well completion

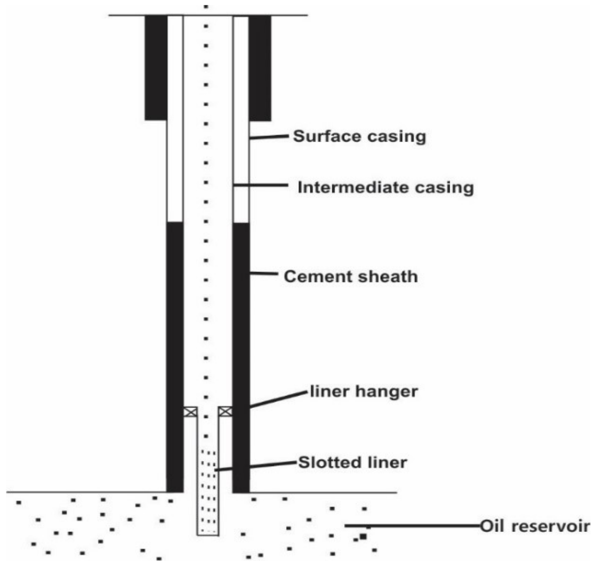
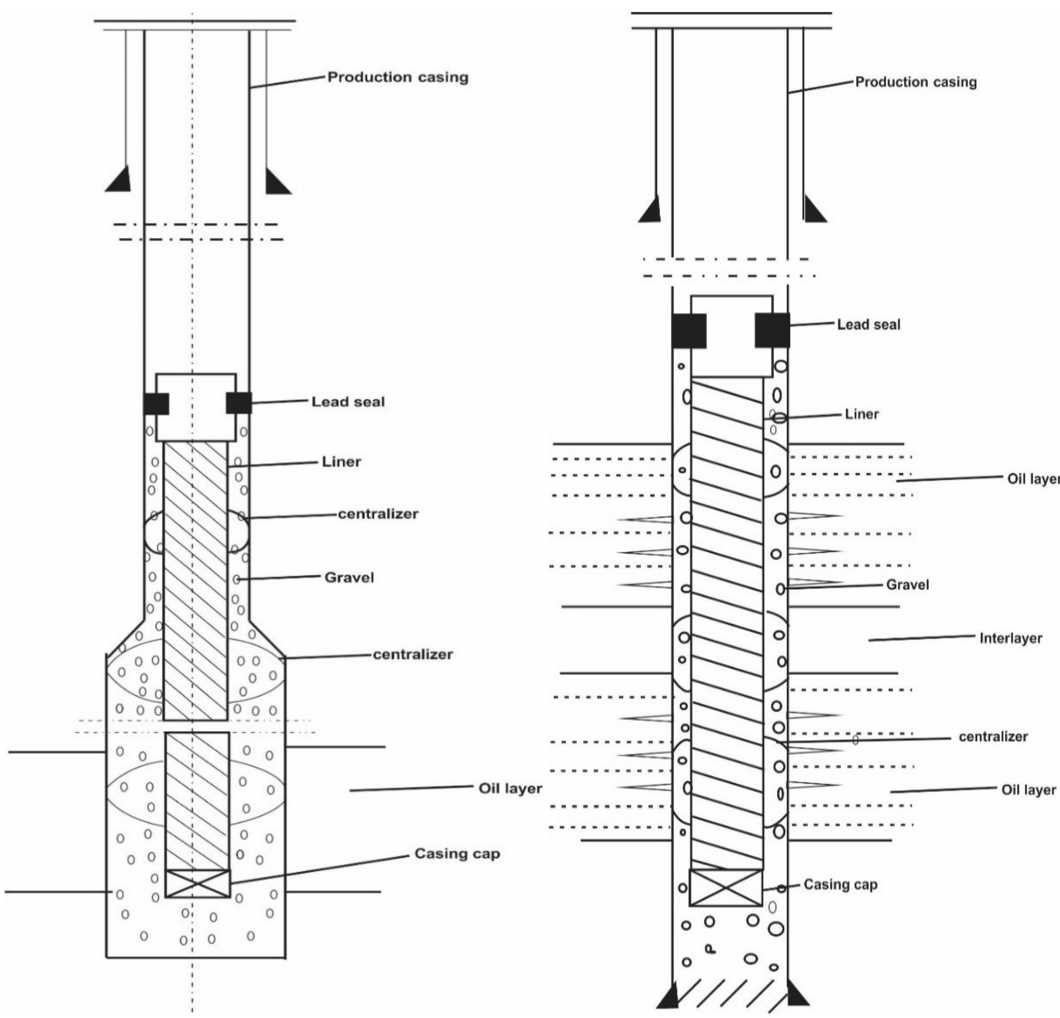


Figure A1. 3 Slotted liner well completion



(a) Open-hole gravel pack (b) Cased-hole gravel pack

Figure A1. 4 Gravel pack well completion

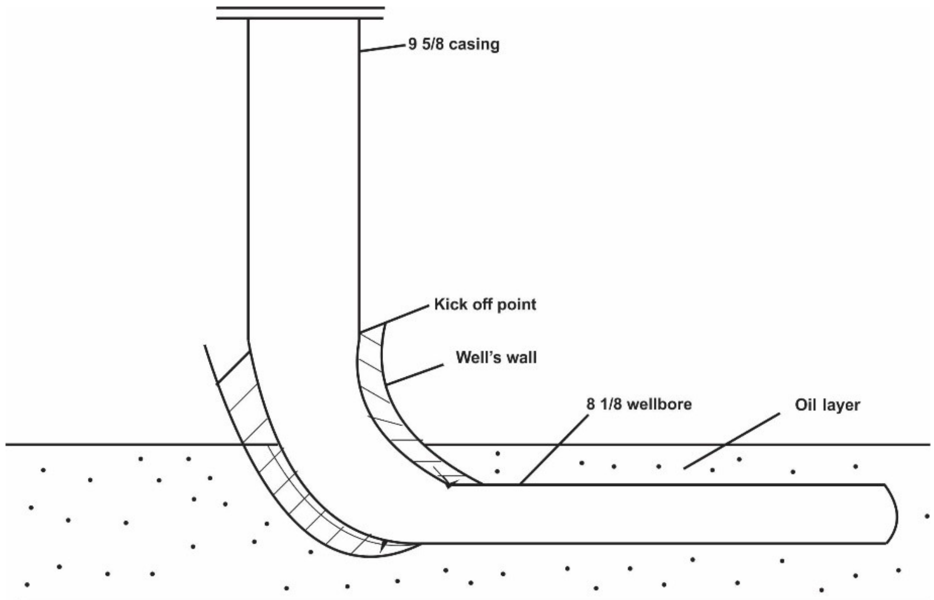


Figure A1. 5 Open hole completion for horizontal well

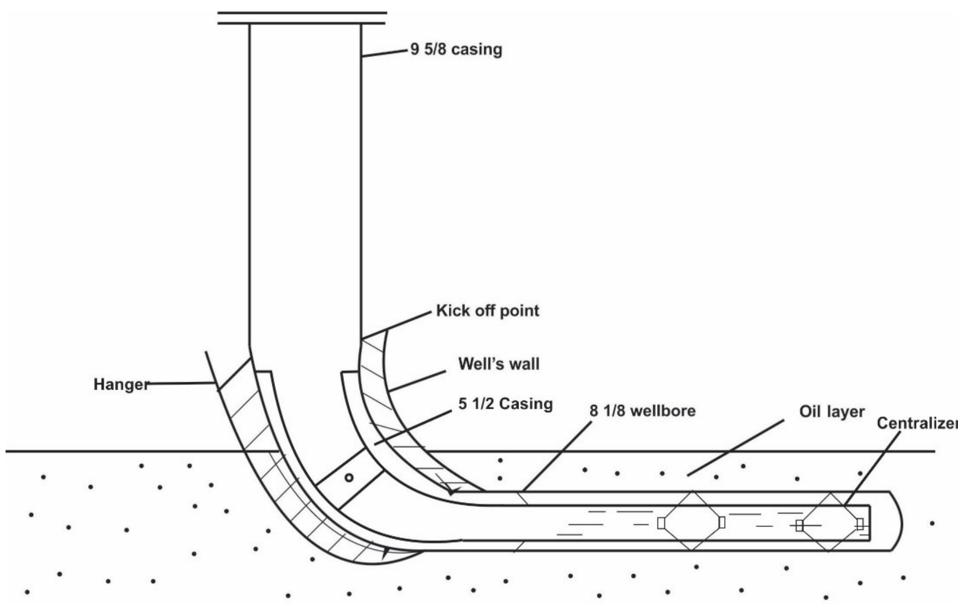
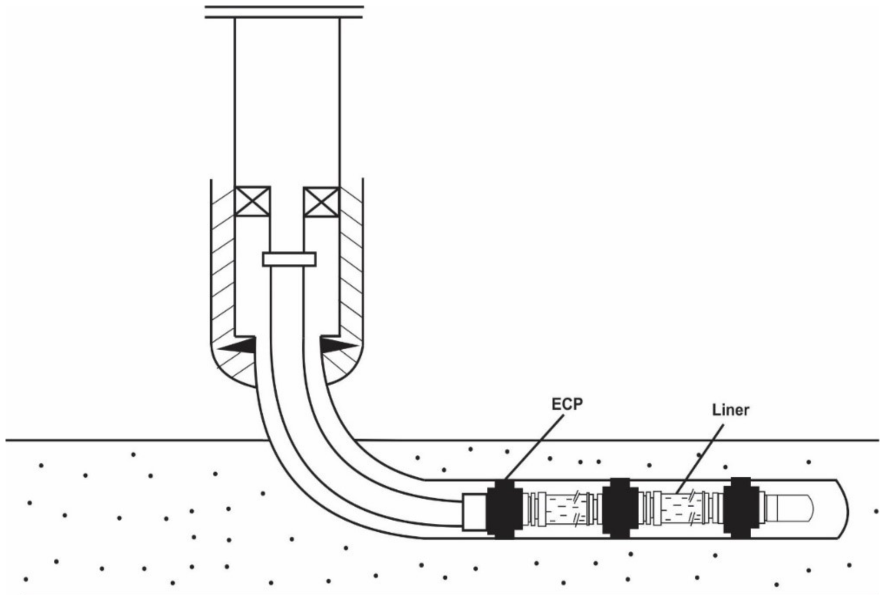
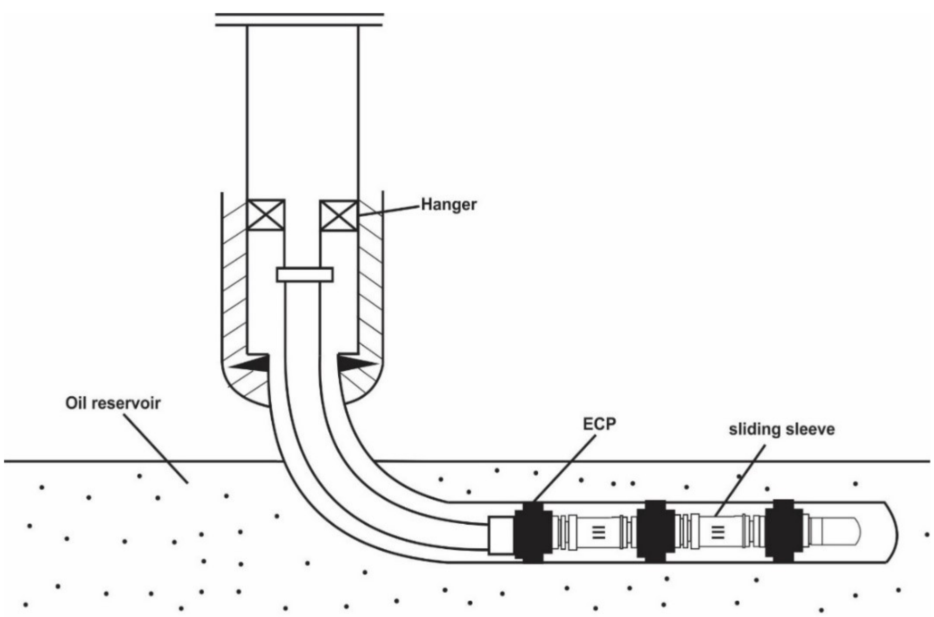


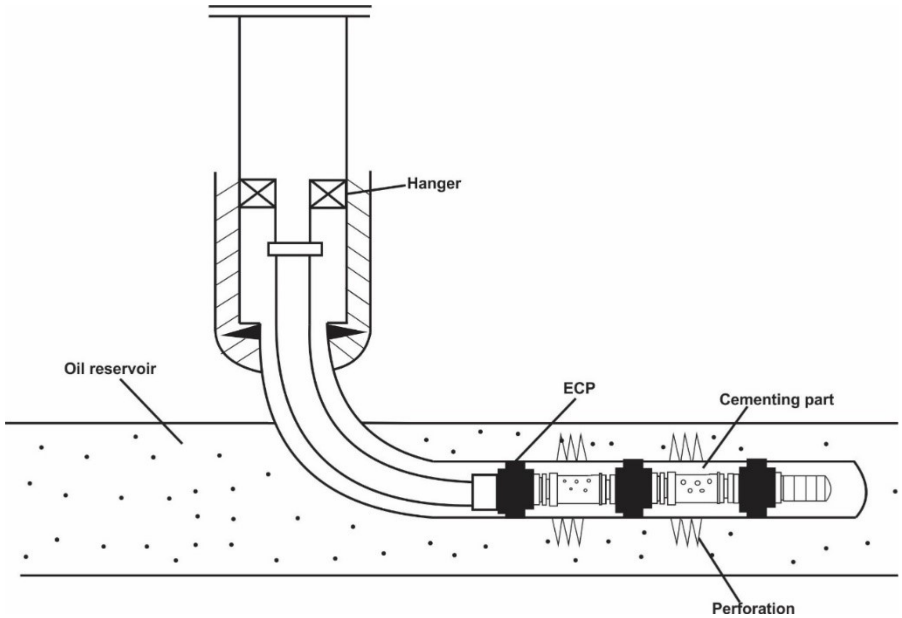
Figure A1. 6 Slotted liner completion for horizontal well



(a) Slotted liner with ECP



(b) ECP with sliding sleeve



(c) Cased hole with ECP

Figure A1. 7 ECP completion for horizontal well

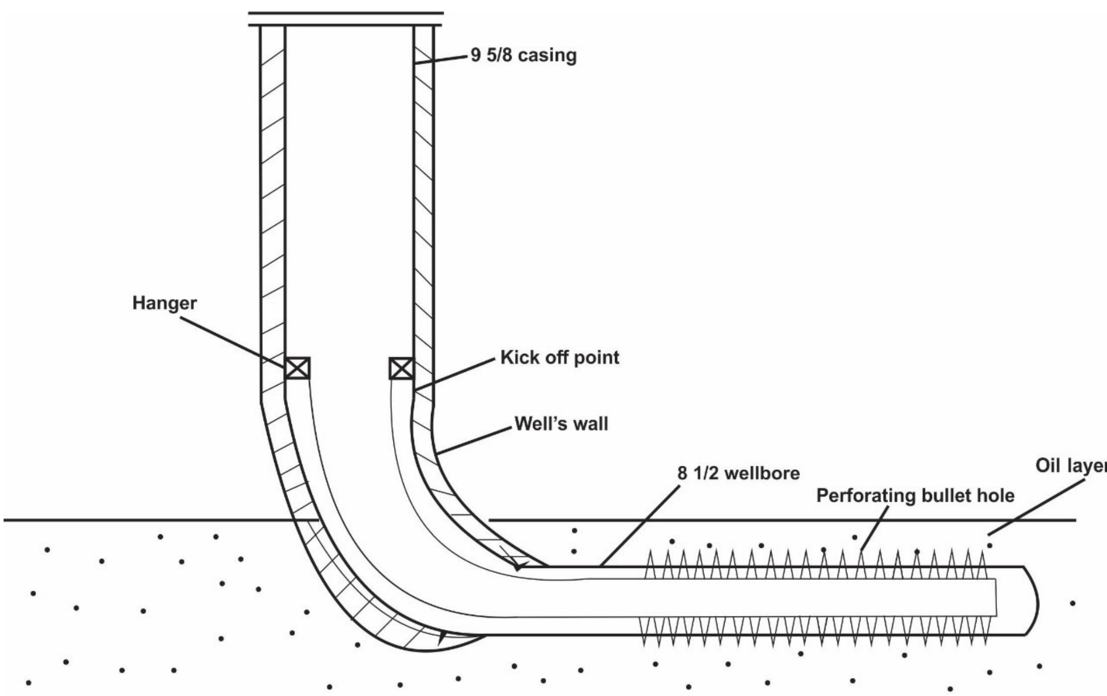
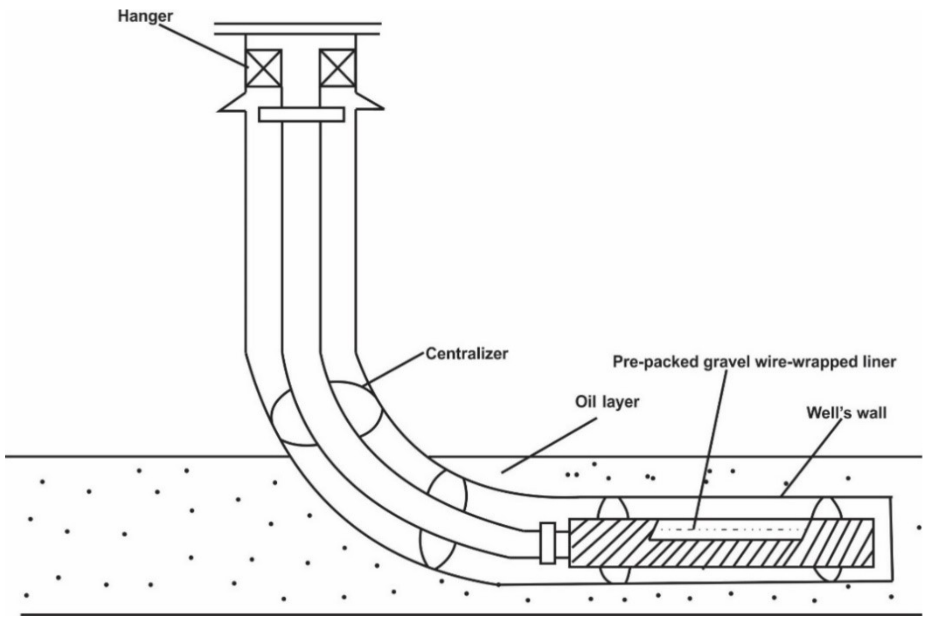
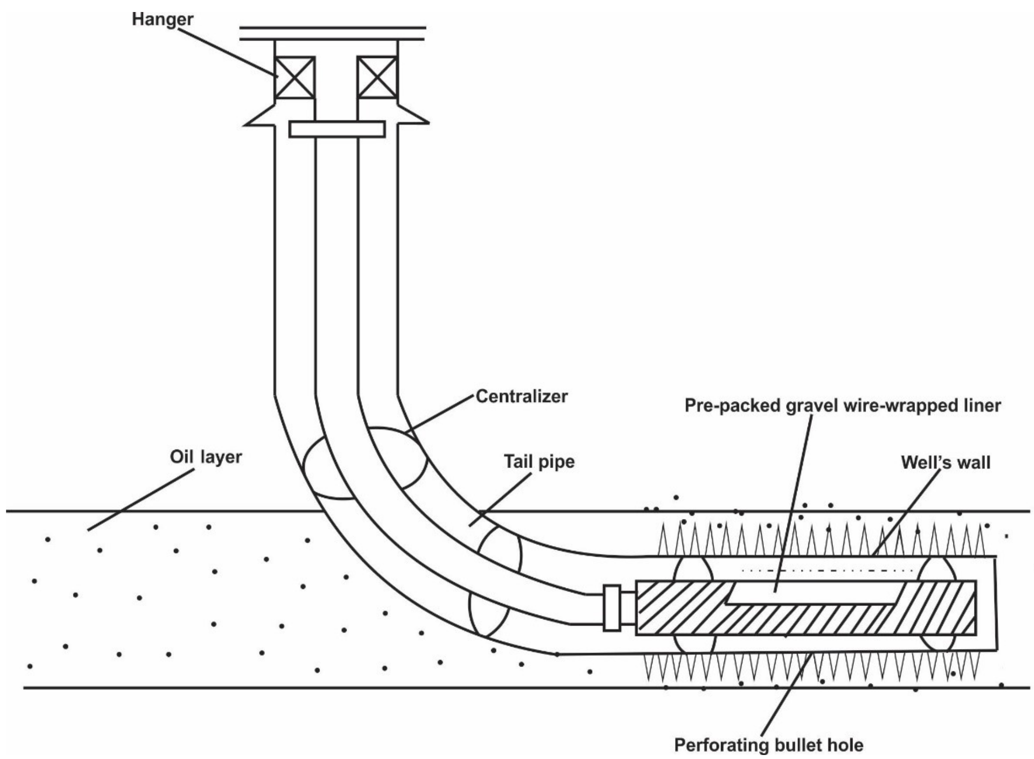


Figure A1. 8 Cased hole completion for horizontal well



(a) open hole completion with pre-packed wire-wrapped liner



(b) cased hole completion with pre-packed wire-wrapped liner

Figure A1. 9 Grave pack completion for horizontal well

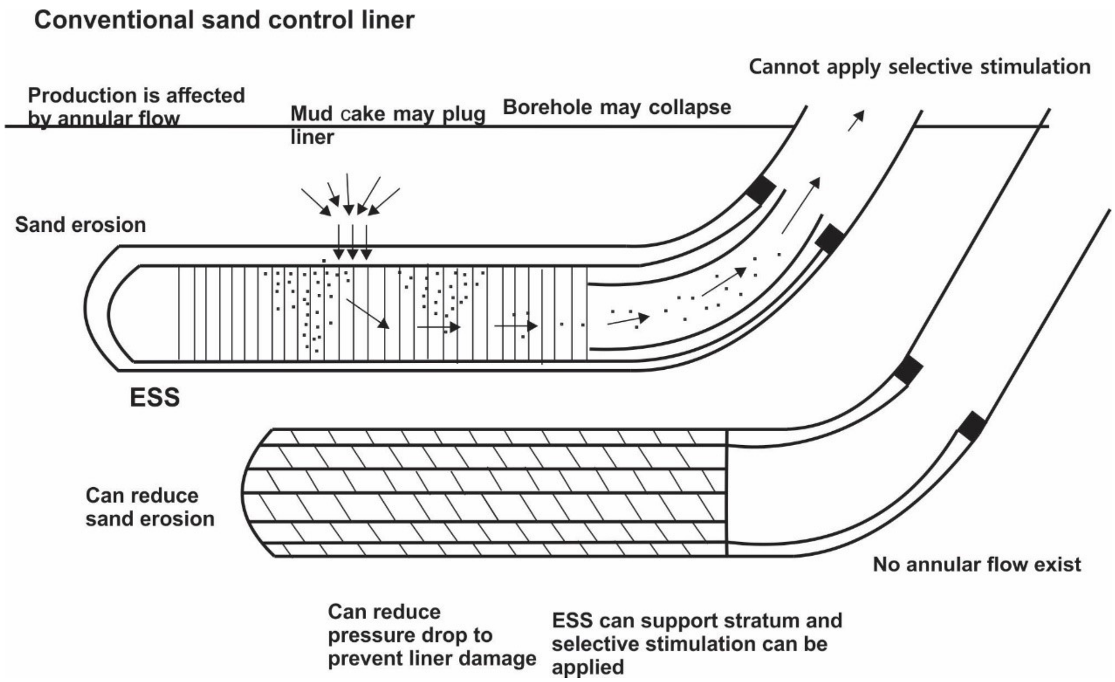


Figure A1. 10 Parallel table of expandable liner and conventional sand control liner