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Manufacturing Software Prototype for applying fuzzy MCDM in Well completion optimization

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Abstract

Well completion is the important system to put the well into the production phase. This well completion engineering system is complex engineering which requires reservoir drilling, cementing of the well, installation of the completion systems according to the well specifications, and then finally initiate the production phase of the well. Due to the major role in the production, stability and life of the well, the oilfields economic benefits are much influenced by the well completion methodology selection. For well completion selection we have various models and specific methodologies, but it is proven that all the selection models are partial due to enhanced focus on quantitative and numerical indexes for example initial production etc. The expert's opinion has a major role for well completion selection as the selection process is very sophisticated and decision makers from various technological background provide useful information and knowledge which finally can help us to design an optimum well completion design.

In this thesis, I will develop a fuzzy TOPSIS decision making software prototype for well completion models selection. I will use linguistic variables instead of crisp values for prototype development due to the data inadequacy to solve the real world problems, and also human beings are not good in judgments and preferences where they have to estimate the exact numerical values for their decisions. So, the use of linguistic variables seems to be more realistic approach where I can rate and weight each criterion for completion models in terms of linguistic variables for assessment.

A case study is discussed in the Chapter 5 to select the well completion model for the Iris production field. Iris field is located on the North Continental Shelf and to the west of Morvin field. Iris reservoir properties indicates that it is HPHT well and it belongs to the Garn formation of Middle Jurassic age. A decision-making system, Fuzzy TOPSIS, developed in this thesis will be applied on the Iris production field to select the lower completion, middle completion, and upper completion.

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My fellow students, along with my supervisor, have contributed well to share knowledge and values. I have experienced an exponential learning curve for academic writing and advanced research work.

Finally, I would like to say special thanks to my parents and my wife for supporting me in all aspects of life throughout my master's degree in Norway.

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Abbrevations

MCDM	Multi-criteria decision making
TOPSIS	Technique for order of preference by similarity to ideal solution
ELECTRE	Elimination and choice expressing the reality
AHP	Analytic hierarchy process
MODM	Multiple objective decision making
FPIS	Fuzzy positive ideal solution
FNIS	Fuzzy negative ideal solution
MOPA	Multi Objective Programming Approach
PROMETHEE	Preference Ranking Organization Method for Enrichment
ECP	External Casing Packer
HSE	Health, safety, and environment
EPI	Environment Protection Index
SODM	Single-Objective Decision-Making
ILCBA	Integrated lower completion barrier assembly

1 Chapter 1: Introduction

1.1 Background

The interface developed between the reservoir and the surface production facilities are most commonly known as completions[1]. After the well has been drilled successfully, the completion designer's make sure to convert it into the safe and efficient production conduit as well as injection conduit for well intervention activities. It is an important to consider the geological properties of the field along with the technical requirements for extraction of the reservoir fluids to build the effectual connection from wellhead to the reservoir.

Although the completion engineers are not the only important decision maker on the oil and gas fields, but it is certain that completion team has to interact with people from wide range of disciplines e.g. drilling engineers, geologist, Petro-physicists, service sector team, management, and commercial analysts etc. In Fig 1.1 (Jonathan, 2009), it can be observed that how necessary it is for completion designer to work in teams and handle the critical interactions for their operations to make successful for optimum designs.

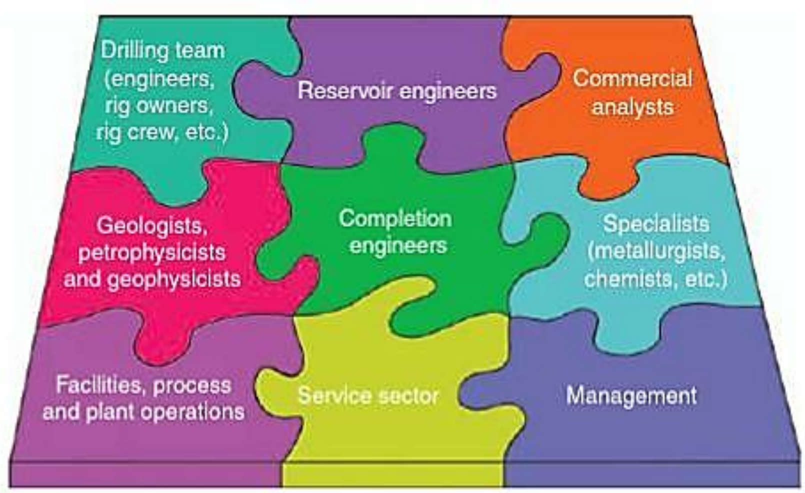

Figure 1.1 The interaction map of well completion engineers (Jonathan, 2009)

The well completion method selection is very critical in terms of safety, environment, and business point of view. The well's productivity, life, and stability are directly influenced by the well completion design selection which can have a huge impact both on the economic value of the oil field and the safety of people and environment. In well completion designs the safety is certainly critical. In past we have cases where poor completion designs have led to the loss of human life as well as the sharp decrease in the production[1]. From energy industries perspective these are the huge losses. The most important point to consider during risk assessment is that installation procedures should not be the only assessments, but we need to highlight any risks included in the proposed completion models which can have direct impact on business, safety, and environment. The impact and likelihood of each risk can be categorized as shown in the Fig 1.2 (Jonathan, 2019).

Figure 1.2 Risk Assessment

In well completion designs there are trade-offs of benefits. For example some designs have lower costs involved, others are more beneficial in productivity or leads to low risk[2]. Multi criteria decision making (MCDM) is very useful technique to deal such situations where it is tough competition to choose and analyze the various criterions for completion modelling and to qualitatively analysis of decision makers conflicts[3].

In Fig 1.3 (Energy Education), the two major types of wells are shown. One of them is the vertical well and the other is horizontal well. The different kind of wells are drilled according to the reservoir characteristics. The one of the major reasons to drill a well horizontally is to increase the contact area with reservoir to get more production of the underground hydrocarbons, to recover the heavy and residual oil[4]. For naturally fractured reservoirs the horizontal wells are preferred. In recent years, the technological development in completion methodologies has huge benefits with useful outcome for both type of wells; horizontal and vertical. These recent developments have proven results to protect the strata of reservoir, enhancement in recovery ratio and overall production of the well. The following are the five commonly used completions:

- Open hole completion
- Perforated completion

- Slotted liner completion
- Gravel pack completion
- EPC completion

The above-mentioned basic completions techniques can be coupled together to achieve the desired results because in complex reservoir geology it is very challenging to complete the tasks by using only single type of well completion. In Gulf of Mexico in 1998 the Baker Oil Tools company had to extract heavy oil from the shallower strata. After careful observation and thorough decision making process, they decided to combine open hole completion with gravel pack completion to successfully finish the large open-hole displacement well[5]. This technique has also been applied by Texaco company. They developed the procedures and strategies after running the physical simulations of wellbores and obtained data from these simulations[6]. The Texaco company was able to mitigate the sanding problems in horizontal wells with abnormal length. This kind of wells actually causes serious issues for gravel packing. In one more case study at the Gulf of Mexico, the Schlumberger and Baker-Hughes experienced the high failure rates in screened completions for horizontal wells[7]. The service and operator companies tried to narrow down the severity of the problem, its major causes, and achievable solutions. The case study proved that the combination of gravel pack and wire-wrapped completions made it possible for successful completion of the series of wells after proposed solution[7].

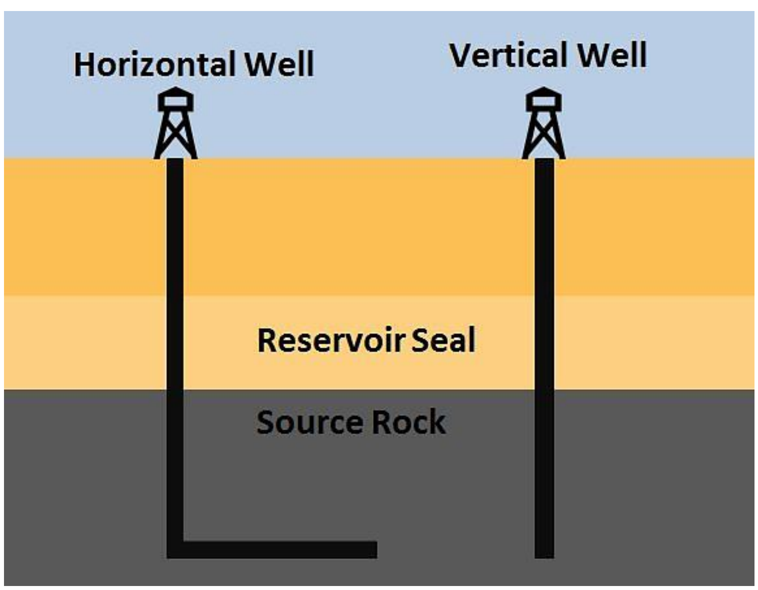

Figure 1.3 Vertical and Horizontal Well (Energy Education)

For many years many new technologies have been evolved and implemented in the oil and gas industry for larger fields to maintain or increase the overall profitability. Intelligent well completion is new and progressive technology[8]. The main advantage of intelligent well completion is that it can send real time downhole information to the surface[9]. It is a system of permanent downhole sensors and the downhole flow valves which can be controlled remotely[9]. By this system we can get real-time information of subsurface parameters like pressure variations and temperature. Production management is also possible in real-time in this completion system[9]. Despite of the various advantages of the intelligent well completion it can present some challenges compared to the conventional completion techniques. It is understandable that it is complex technology and requires in-depth pre planning before applying. The most common challenges which has been reported are the downhole barriers[10], issues with tubing hanger, complex and expensive technology[11], data handling and management etc.

Although the new technology and skills have overcome various challenges in well completions procedures, but it has also made oil and gas industry to be less flexible and most of the time they focus more on proficiency. This the primary reason that most of the well's completion models are using perforated completion. The lack of adoptability then directly affects the economics due to decrease in recovery ratio and well productivity. In this scenario, the multi criteria decision making (MCDM) systems should be implemented to well completion model selections for more adoptive approach.

1.2 Objectives of Research

The only path available for successful extraction of reservoir fluids and then the plug and abandonment of the wells is through the wellbore. In this regard, the well completion plays a vital role in well integrity through-out the life cycle of the well. In oil and gas industry, the well completion is a very sensitive decision-making process because any kind of problems can halt the production activities and can cost immensely. Wellbore stakeholders understand that in post-drilling activities the feasible design of well completion with high operational magnitude is directly correlated to the overall performance, technical management, and revenue of the oil and gas fields. Most well completion model design approaches for designing and implementation rely heavily on the numerical indexes like the substantial operational cost, initial production values. This numerical approach for well completion selection is too ideal and expert opinion in the model selection is ignored. Hence, the well completion selection process needs to be refined where the comprehensive approach is required to deal with this complex selection process.

Due to a lot of application of crude oil in downstream industry and everyday use of these products in common life it is imperative to consider those designs, operations and equipment's which are useful to boost the productiveness and minify the cost of the processes in the upstream sector. Decision making processes needs to be taken under consideration and implemented when selecting the tools, equipment's, designs and installation procedure for well completion models. This decision-making process can immensely influence the costs, well productivity, well intervention time and costs related to well maintenance. Due to the involvement of complex technicalities and people from various background in well completion selection process the decision-making systems helps to find out the most suitable alternatives for well completion models which can be beneficial for both the upstream and downstream industry.

The primary objective of this research is to build a multi-criteria decision-making approach for the well completion selection. In MCDM approach we can consider the range of criteria and then we evaluate all the alternatives available for well completions modelling and selection. This approach considers all the preferences, assumptions, and useful data for making consistent and systematic decisions. In this research, the Fuzzy TOPSIS (Techniques for Order of Preference by Similarity to Ideal Solution) approach is applied because this decision-making technique is very precise, and the results of outcome are reliable to implement practically. The chosen alternatives in this approach are backed by expert's technical knowledge and the MCDM approach makes it possible to rank all the alternatives in a systematic way. Another positive aspect of this decision-making approach is that the ranking of the criteria for well completion models is composed of expert's opinion from wide range of discipline e.g. geologist, economist, drilling engineer, production engineer, reservoir engineer, environmentalists etc.

The summary of the main contribution in this thesis work is combined as follow:

- The review of well completion technologies in previous literature. The optimization of well completion in that literature is reviewed and the comparison of their advantages and setbacks have been useful for building the research foundation for well completion optimization.

- The use of MCDM techniques in oil and gas industry have been discussed in this research work to thoroughly understand the practical application of decision-making process in industry. It will help to further eliminate the shortcomings in decision making process.
- Comparison of the available MCDM techniques have provided the useful information to understand which techniques is more feasible during well completion selection process under certain conditions. Their advantages and disadvantages are also discussed.
- Development of the Fuzzy TOPSIS software prototype for well completion selection. The various criteria's and alternatives have been inserted in the prototype to provide the comprehensive selection from various methodologies, tools, techniques, and installation process.
- The software is very flexible and can fulfill the requirements of specific company's needs. The linguistic variables are used to weight each criteria and alternative as the crisp numbers are very challenging for human beings to handle during decision making process.
- In Fuzzy TOPSIS, the alternatives are ranked based on the decision maker's input. All decision makers input weight each criterion and each alternative are given decision maker linguistic variable. The alternatives are ranked based on the expert's opinion and the alternative with higher order preference is considered more closer to the ideal solution.

2 Chapter 2: The Review of the Previous Literature

2.1 Analysis of Decision-Making Procedure

Decisions are compulsory ingredients in all types of organizations and industries. The proper understanding of the organization values and its goals are important factors to be considered by decision makers to achieve the set goals as decision making process is very systematic and it's the duty of the decision maker to analyze all the available alternatives with thorough understanding. The decision maker can be anyone in the organization from the managing director of a company, project leader, engineer to the economic analysts, and their level of understanding decision making process may vary from each other[12].The decision making process involves people from various discipline and the cost of malfunctions in decisions could be very expensive as it can affect all the procedural instruments[12].

We classify the decisions problems in three level which includes structured problems, semi-structured problems and third one is unstructured problems[12]. Ill structured problems are the last two one, semi-structured and unstructured, and they cannot be solved using standard mathematical models and solutions. The classical mathematical models used to solve the decision problems which are well structured[13]. To resolve the ill-structured problems for decision making the involvement of fuzzy set theory helps to sort out the ambiguousness in the data and includes human judgement with more justifiable able and systematic approach. The well completion decision making process is usually semi-structured problem that's why it is considered challenging to select optimized well completions due to the nature of the problem, involvement of human judgement and integration of mathematical models.

2.1.1 Overview of MCDM

In most of the decisions the criteria to be considered are more than one which makes it very demanding and challenging to make decisions in complex situations. Although to make decision is every common from individual level to large organization level but the systematic approach to deal with problems and then make suitable decision involves various steps for clear outcomes. As we discussed earlier most of the problems, we face are semi-structured and they require expert's judgement and mathematical modelling, so the Multi-Criteria Decision Making (MCDM) is one of the approaches which provides operational models in decision making. It aids both qualitative and quantitative handling of the criteria, manages the conflicts among the criteria involved in a problem[14]. This MCDM method, additionally, also provides a way to assess the trade-off among the criteria so to prioritize the given criteria with the best possible outcome. The Fig 2.1 shows the general procedure involved in MCDM. In 1896, Pareto introduced the optimality-based concept which is the root cause of this MCDM process[15]. After this initial idea, the other scientist contributed in Preto work and brought out the concept of efficient-point[16] and optimization of the vectors in mid-20th century[17]. Only after the efforts and research work of Charnes and Cooper in object-programming the MCDM became the normative methodology in scientific decision making[18]. Overall, this approach can be useful in its application for the better choice and ranking of alternatives during the decision making in many fields.

The major attributes of the MCDM related problems are mentioned below[19]:

- It is very hard to compare the criteria as in MCDM there is no standard measure of unit for comparison of criteria and alternatives.
- Although the optimization is the major concern in decision making, but it is extremely challenging to optimize all the objectives involved in MCDM problem.
- It is necessary to contemplate both qualitative and quantitative criteria.

Due to the above-mentioned characteristics of the multi-criteria decisions we have two methods called Multi-Objective Decision Making (MODM) and the Multi-Attribute Decision Making (MADM). In these methods we optimize the set of objectives and alternatives against the suitable constraints and criteria[20].

The solution methods of MCDM are following[21]:

- Unique Synthesis: The expert's opinion is gathered and inserted into a function for optimizing it. Example of this method are Analytical Hierarchy Process (AHP) and TOPSIS.
- Outranking Synthesis: In this method, decision maker opinions or preferences are shown in outranking relationship. Elimination and Choice Expressing Reality (ELECTRE) and

Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) fall in this category.

- Interactive Local Judgement: Decision maker preferences can be given more data due to flexibility of this method in calculation steps[22].

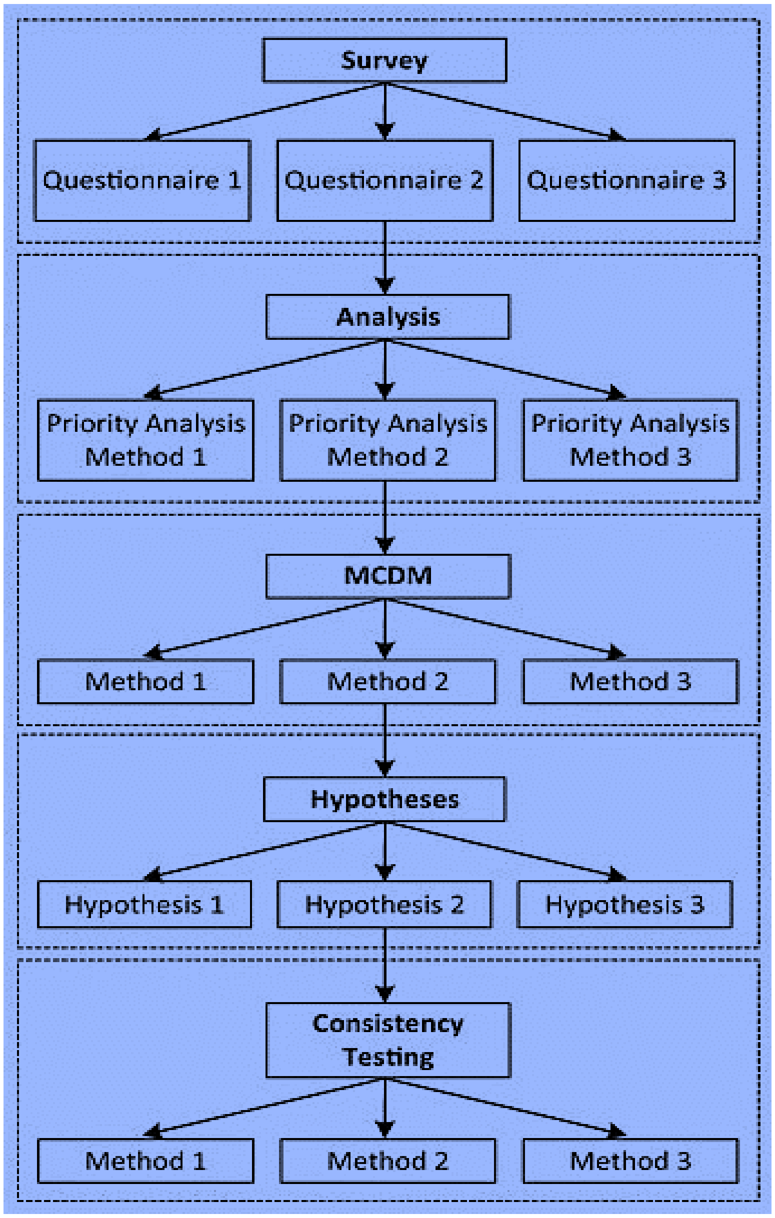

Figure 2.1 MCDM Flowchart [23]

2.1.2 Overview of MODM

Multi-objective Decision Making system is applied in situation where there are many possible outcomes for each objective. In MODM, unlike SODM, the relationship between the objective is not so simple but it is based on complex relationship which leads to rank the decision maker preferences[24]. In reality, we cannot make decision based on single-objective decision-making system as the goals of big organization involves multi-level process to achieve their objective so in that case MODM system comes in handy to deal complex decision-making process.

The various models of MODM used by experts are discussed below.

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

In 1981, the researcher Hwang and Yoon worked on to solve the multi-criteria problems and come up with this technique called TOPSIS[25]. This is very practical method for solving problems for decision making point of view. In this technique the geometric distance of alternative is calculated. Each decision maker give weightage to individual alternative, then TOPSIS system calculate the geometric distance of each alternative with respect to the ideal solution[26]. There are two types of ideal solution in TOPSIS, one is knowns as positive ideal solution (PIS) and the other is negative ideal solution (NIS). The alternative closest to the positive ideal solution is ranked higher and the priority is given to this alternative for final decision-making process. TOPSIS is very practical approach to deal real-life problems.

Benefits of TOPSIS[27]:

- The process of computation is uncomplicated.
- Data handling is simple and in TOPSIS it is straightforward to utilize the original data.
- In TOPSIS the final choice is logical based on human judgements.
- Sample size is not an issue in this technique.
- Polyhedron shows the performance of all alternatives in visual form.

Drawbacks of TOPSIS:

- Complication of ranking reversal in case of adding new alternatives in the existing system.
- Normalized matrix is required in TOPSIS, but for complex matrix it is not an easy task to get the PIS and NIS values for each alternative.
- Symmetrical alternative on the ideal solution line are impossible to compare.

II. Elimination and Choice Expressing the Reality (ELECTRE)

Benayoun, Roy and Sussman put forward the very first proposal of ELECTRE methodology. There are three main versions of this technique to handle the variety of problems: sorting problematic, ranking problematic, and choice problematic. In choice problematic ELECTRE, the good alternatives are included in the set for decision makers to choose among them. The models where the ranking of alternative is asked uses the ranking problematic. Pre-defined categories are made for alternatives in sorting problematic. ELECTRE technique is performed in two main steps, where the first step, called building outranking relation, compares the whole set of alternatives in depth and the second step, known as exploitation procedure, explains the outcomes of the building outranking relation[28].

Benefits of ELECTRE:

- Elimination of less important alternatives can save time.
- There is no use of abstract scales in outranking model[29].
- Useful technique to apply for decision making when the data contains liars[30].

Drawbacks of ELECTRE:

- Useless evaluation of criteria even though it has no weightage[31].
- Requires a lot of information and data to initiate the process.

III. Multi-objective Programming Approach:

A. Charnes and W.W. Cooper introduced this MOPA approach in 1957[32]. In MOPA, the values are assigned to the objective function, and under some constraints the solution is found which is nearest to the target value. To handle deviation of the objectives, the new variable, deviation variable, is used. In short, MOPA converts the multi-objective problems into single objective[9].

Benefits of MOPA:

- The optimization of individual objectives is possible when other objectives are being constrained[9].
- Priority factor shows the worth of each objective.
- Swap of the constraints is possible in MOPA e.g. from hard to soft constraints.

Drawbacks of MOPA[9]:

- Not suitable for problems where the objectives and constraints are non-linear functions.
- Functions of objectives and constraints are not able fit in function always due to fuzzification.

IV. Entropy Method

The concept of entropy was taken from thermodynamics for MODM process in 1948 by Shannon[33]. In systems which are higher in disorder shows that they have high values of entropy[34]. In decision making process the indexes are provided with relevant information. If the given index has more information, it means there less chances of uncertainty and it indicates this index have lower entropy[9]. This index then has higher weightage in the system as compared to those having higher values of entropy. Due to much rely on information and data for calculation this method is very less influenced by human judgements so there are rare chances of human error[9].

Benefits of Entropy:

- For weighting each criterion in the system, it remains unbiased[35].
- Conflicts in the objective criteria are easily handled by this method[35].
- Assessment of the efficiency, cost or benefit is possible quantitatively[35].
- Discrimination of criteria in this system is represented[9].

Drawbacks of Entropy:

- Because the expert judgement is not much involved, so the distortion of criteria weight is an issue of entropy method[9].
- Lack of mutual relationship among criteria.
- Decision matrix consist of large quantity of alternatives[36].

V. Analytical Hierarchy Process (AHP)

In 1970s, Thomas Saaty gave the concept of AHP for solving the decision problems which were irreversible in nature and complex at the same time[9]. The working mechanism of AHP is to transform the subjective assessment of relative importance to overall weight and score[37]. The comparison matrix is one of the useful aspects of AHP[9]. But there are chances of inconsistency in AHP.

Benefits of AHP:

- Complex expert system is not required in AHP[38].
- Both kind of problems can be solved by AHP; qualitative and quantitative.
- Inconsistencies are manageable, so it is well flexible system[39].
- AHP makes it easier to perform pairwise comparison because of criteria hierarchy[40].
- Group decision making based on consensus is encouraged. For that the geometric mean is calculated[41].

Drawbacks of AHP[9]:

- Number of evaluations may increase for complex scenarios.
- 1 to 9 scale sometimes hard to differentiate.
- In AHP we may face the issues of rank reversal.
- Elements dependency to each other can be problematic in real-world problems.

2.1.3 Overview of MADM

Multi-attribute decision making theory was first used by Churchman et al. in 1957 where it was applied on a set of problems by using the method of additive weight[42]. In this technique, the decision makers goal is to select the most suited alternatives from a given set of alternatives. Evaluation process of the alternative is carried out through multiple attributes. This method, MADM, has a wide range of application in industries like medical, engineering, construction, and management[42].

I. Analytical Hierarchy Process (AHP)

Except the hierarchical structure of AHP in MADM, it works the same way as it does in MODM method. Fig 2.2 is shown below.

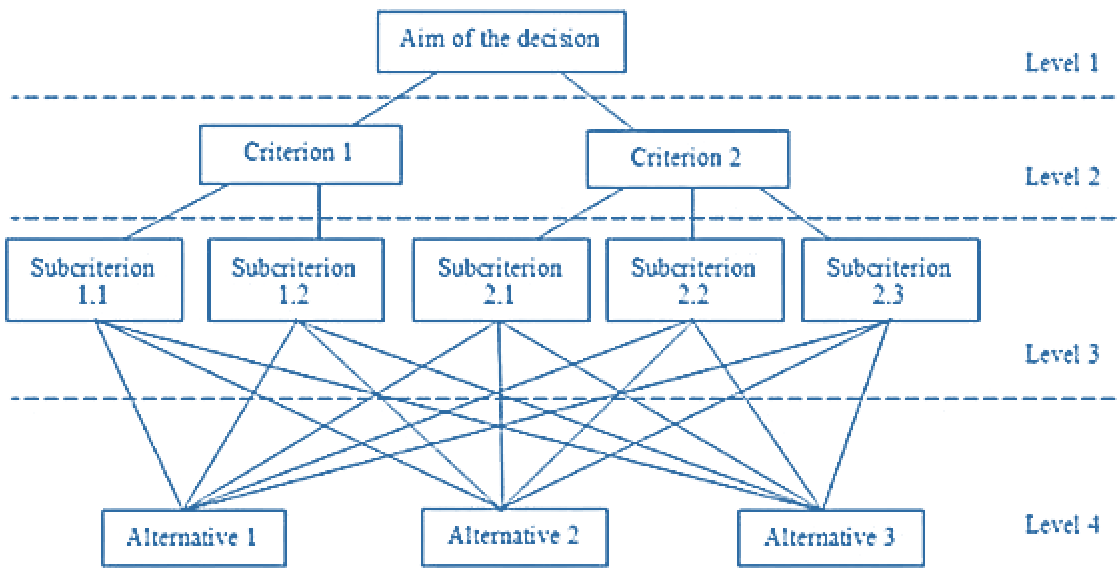

Figure 2.1 Analytical Hierarchy Process

II. Preference Ranking Organization Method for Enrichment (PROMETHEE)

In 1982, Brans presented the PROMETHEE, the further developments in it, 1985, were the contribution of Vincke and Brans[43]. Two methods are usually performed for the ranking of alternatives by PROMETHEE 1 and PROMETHEE 2[44]. The former method is put in place for alternatives where partial ranking is involved, and the latter is for complete ranking of the alternatives[44].

Benefits of PROMETHEE[9]:

- Reversal ranking is not an issue in PROMETHEE.
- It is much stable as compared to ELECTRE.
- Fuzzy information and uncertainty are possible to handle.
- Nondimensionalize and normalize indexes are not part of this method.

Drawbacks of PROMTHEE[9]:

- Weight determination is huge issue in PROMTHEE which can cause problems for decision makers.
- Structural analysis lacks in efficiency.
- Sometimes reversal ranking could be a complication in the process.

III. Grey Relational Analysis

Deng brought up the idea of GRA[45], which is a coherent method to solve the decision issues where we have insufficient and unknown data. The way of categorization of information in GRA is so simple, as it categorizes the accurate information as white, and black is reserved for information which is incomplete. Though the real problems are not differentiated completely in terms of black and white category, while GRA system uses the grey information to manage the situation in these two extremes[46]. A continuum is created from black through grey to white[46]. Finally, depending upon the position of each situation on continuum, it proposes various solutions. The ideal solution for given problem will lie on the white continuum.

Benefits of GRA[9]:

- Based on the original data and requires simple calculations.
- This system is able to perform well in case of situations where necessary data is hard to get.

Drawbacks of GRA[9]:

- Index optimal values are challenging to get.
- Alternative doesn't present any kind of relationship.

2.2 Role of MCDM in Energy Sector

In oil and gas industry, well completion is the backbone of the three phases drilling, production, and abandonment. Proper well completion process is carried out through the well completion engineering. Well completion engineers have to interact with management and other experts from different fields to design and install the proper well completion for a given well. Due to its role in oil and gas industry, it has become norm to apply decision making models for optimized selection of the well completion methods.

2.2.1 Decision Making Based on Experience and Knowledge

According to Johnston et al (2008)[47], the well completion is a multifaceted problem which needs the collaborative approach of people from various backgrounds. The sharing of knowledge and experience is key for good selection of well completion. The authors of this study suggested the people from these disciplines, geology, economy, drilling, reservoir, petrophysics, contribute majorly for good well completion design for specific formation[9].

Optimum selection of gas reservoir by Jia et al. (2016)[48] was actually based on experience. They built this well completion selection model for particular gas reservoir. The basic understanding of the formation was taken into consideration and also the geological model of the gas reservoir was analyzed. The only shortcoming in this methodology was the lack of weighting of some important individual factors which could have played a major role for more well-established design of well completion[9]. Only experience based decision-making solutions are not much reliable due to the lack of systemization in the process.

Well completion method selection based on set criteria was performed by Idiodemise et al. in 2007[49]. The authors utilized their criteria for completions selection, junction selection or other activities like sand control devices selection[9]. It is simple way for method selection as the influencing criteria have already been proposed and set by researcher for making decision. Some critical factors can cause the conflicts in method selection. Use of gravel pack devices in downhole requires several factors to be considered. Some factors may go in favor of using the gravel packing, while other factors can be in conflict for using such devices. So, it has become obvious that how important is it to assign weighting to each factor to reduce the contradiction among various factors for better method selection.

2.2.2 Development of Flow Chart for Well Completion Selection

It is understood that systematic methodologies are important in oil and gas industry for selection or decision-making process. Such systematic way of selection procedures was published by Ouyang et al. (2006) by introducing the concept of flow chart [50]. They constructed that flow chat so they can finally come out with a cost-efficient well completion method. Their primary focus was to select completion method which was not only cost-effective but also it has good output for production and sand control in wells. In this study, the Ouyang et al. [50] suggested that some of the well completions costs are tangible, while other completion costs are intangible. They made two separate groups for tangible and intangible completion costs. The various factors and items were also included in these categories. But this method is too subjective and general, it cannot be considered to apply in real life situation.

Similarly, in 2003, Sinha et al. [51] also assembled a flow chart after thorough study of different field environments. Case studies from those oil fields were used to find some commonalities. The studies showed that the reservoir characteristics and well architecture relationship have given same characteristics and attributes among these fields. For the flow chart development, the whole well architecture was divided into three categories: completion tools, formation completion, well trajectory. The common attributes of the fields from case studies were put into the flow chart so to select the completion tools, well trajectory, and formation completion. This method sounds more qualitative and have more input of expert’s experience, but it cannot be considered accurate enough.

2.2.3 Application of MCDM for Completion Selection

Using flow chart method for optimized selection purpose is not enough and it has limitation, also the well completion selection process is multi-attribute and multi-objective task so some authors applied the MCDM approach for well completion selection to resolve the issues in flow chart.

Studies of Morooka et al. (2002) [52] established the method for selecting the floating production system. The concept of multi-attribute and Utility Function theory was applied in their model selection. The range of factors were examined and applied in their study for best possible selection of floating system. Those factors were related to the risk assessment, technical domain, cost/benefit and environmental. The downside observed in their study was that it is inconvenient for theory of utility function to establish a model for all the factors in a given problem. So qualitative is only remaining approach for selecting some factors, which is always a setback in decision problems.

Another proposal [53] was given to determine the suitable options for lifting the gas wells by Rehman et al. (2002). Optimized model selection to lift the well was relied on distant based. Various simulation models integrated, like economic analysis and production of well, together to select the optimized option. The optimum case is defined before measuring the distance between the optimum case and given alternatives. The mathematical model then calculates the distance among alternative and optimum case, and the output value of this model shows which option is more feasible to consider for lifting the gas well. Smaller value indicates the best alternative to select.

Grey MADM, TOPSIS, and Fuzzy synthesis [54] systems were combined together to develop a decision-making model. This study was conducted to choose the well completion model for coal-bed methane formation. In this technique the selection process is not too subjective, included both economic and production aspect of field, and the weights of alternatives were considered for well completion process.

3 Chapter 3: Fundamentals of Well Completion and Methodology Review

In this chapter the well completion methods are discussed with respect to specific conditions of the formation. Well completion methods understanding is an important task to set the criteria and define various alternatives when making decision. Individual well completion methods are highlighted in terms of its strengths and weakness and when they are applicable is also discussed in the following section.

3.1 Overview of Well Completion

In drilling process the well completion is an important phase after drilling has been completed to the reservoir zone. The bottom hole assembly is connected to the reservoir zone. The BHA is part of well completion design process which establish a conduit for extracting hydrocarbons. So once drilling phase is done then well completions are installed in the wellbore which initiates the production phase of oil and gas. Well productivity is directly correlated with economic output of an oil/gas field and both these factors majorly rely on the compatible selection of well completion for a given formation.

It is proven facts that variation in completion design can alter the reservoir recovery factor, drainage area, production capacity of reservoir fluids and costs of all post-drilling activities[9]. By keeping in mind all these variable factors, a better approach for well completion design helps to mitigate the risk of loss of hydrocarbons in mistakenly induced fractures in wellbore and formation, also it enhances the probability of average production of all well in the developed field. The overall economic benefits and finally abandonment activities can have a high success rate by proper and systematic approach in well completion design and selection.

Well completion techniques have been improved a lot with the development of technology and research. Conventional well completions may not be of more interest due to increased depth of reservoirs, complex issues being faced during production life of the well, and high demands of economic benefits from energy sector. Two major types of wells, vertical and horizontal, demands different kind of completion to fulfill their working conditions. In the section below, major completion designs are discussed for vertical and horizontal wells.

3.1.1 Well Completion Types for Vertical Wells

i. Open Hole Completion

In this type of completion, the reservoir formations are without the casing and the reservoir fluids directly flow into the production casing which is on top of the formation and fluids go to production facility through wellbore[9]. This type of completions is recommended where the formation lithology is hard enough to withstand the reservoir pressure and it won't fall down into the well bore[9]. Reservoir pressure must also be consistent and have high porosity and permeability for open hole completions. The open hole completion provides large inflow area which ultimately improves the wellbore performance and due to not much use of drilling fluids in the productions zone formations are not damaged badly. Wellbore skin is also recorded minimum in open hole well completions. On the other hand, open hole completions are not recommended to use where formation is loose, and it has sand production issues which can stop the production. Reservoir management is complex task in this completion when uncertain incident happens.

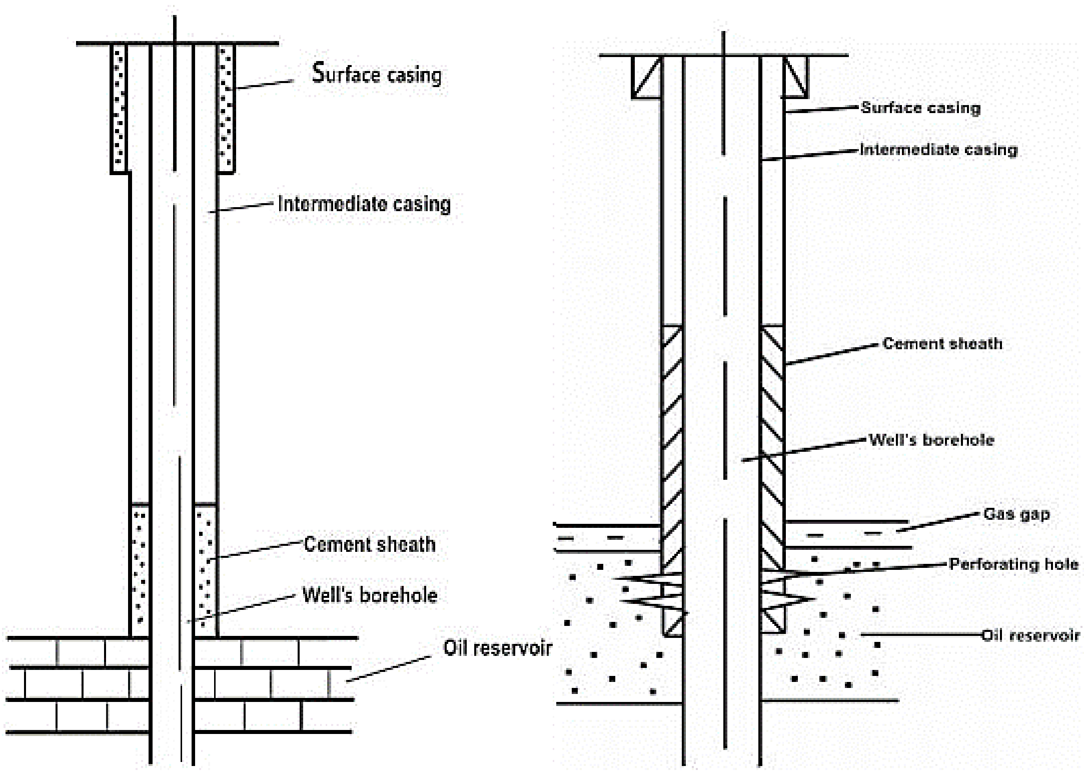

Figure 3.1 (a) Initial Open Hole Completion (b) Compound Open Hole Completion

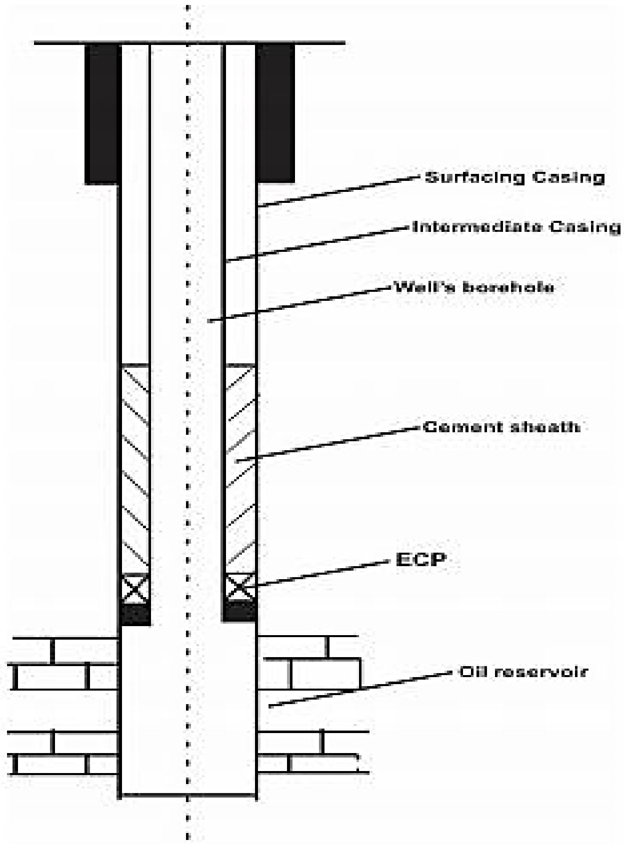

Figure 3.3 Complete Open Hole Completion

ii. Cased Hole Completion

Perforated casing completion has a major use in today's well completion where casing is perforated once it has been set around at the designated zone[9]. Cased hole completion is applied in when the permeability is not much high and hydraulic fracturing job needs to be done in such formation[9]. Also, loose formation issues can be resolved in this completion. Different layers with varying pressure zones are perforated to extract the reservoir fluids and cased hole completion make this activity handle really well. In cased hole completion the zonal isolation is much stable, and it also provides a solution for sand control and water flow into the wellbore[55]. Better reservoir management and well integrity are also the characteristics of this completion. Cased hole completion has not provided much success in highly deviated wells as there is less contact area of bottom hole assembly with reservoir[55]. Stratum pressure calculation is very sensitive in that completions as during perforation it can cause huge risk to the wellbore integrity[55].

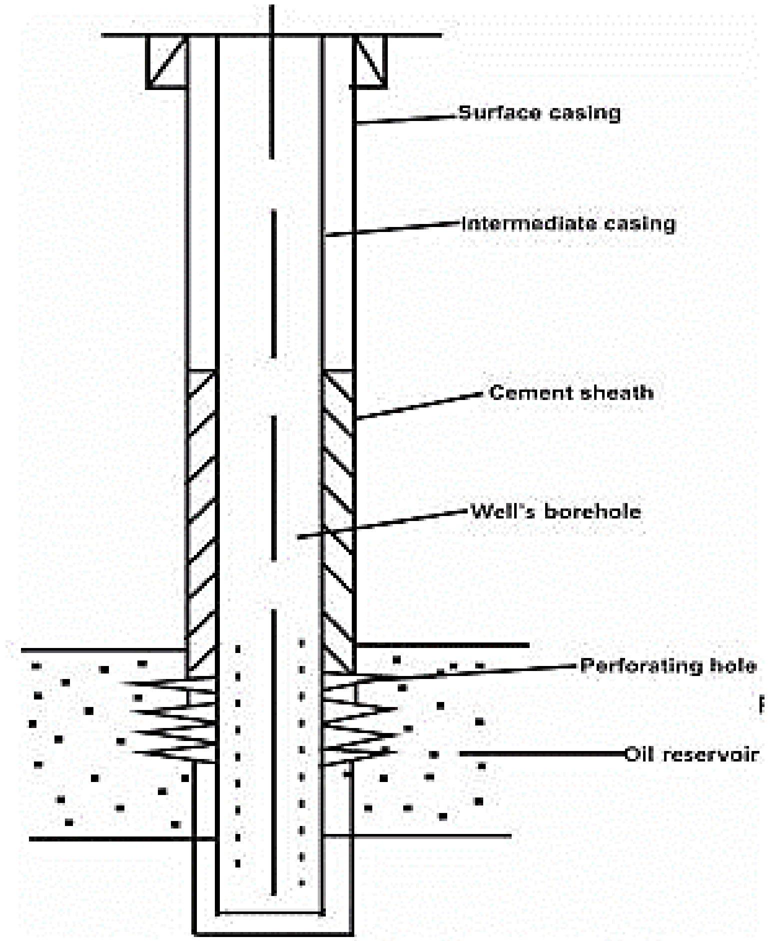

Figure 3.4 Perforated Cased Hole Well Completion

iii. Slotted Liner Completion

It is simple completion to be applied on the reservoir which do not have any sanding issues[9]. Most suitable situation for slotted completion where zonal isolation and stimulation are not preferred[9]. Consistent pressure reservoir can be suitable for this completion type. It is cost efficient well completion technique as the slotted liners are repairable to use again. Use of the cementing mud cause less damage to the oil layers. These completions can also manage the sand production. Oppositely, the slotted liner completion can face sharp pressure drops as it has less area of flow for fluids[56].

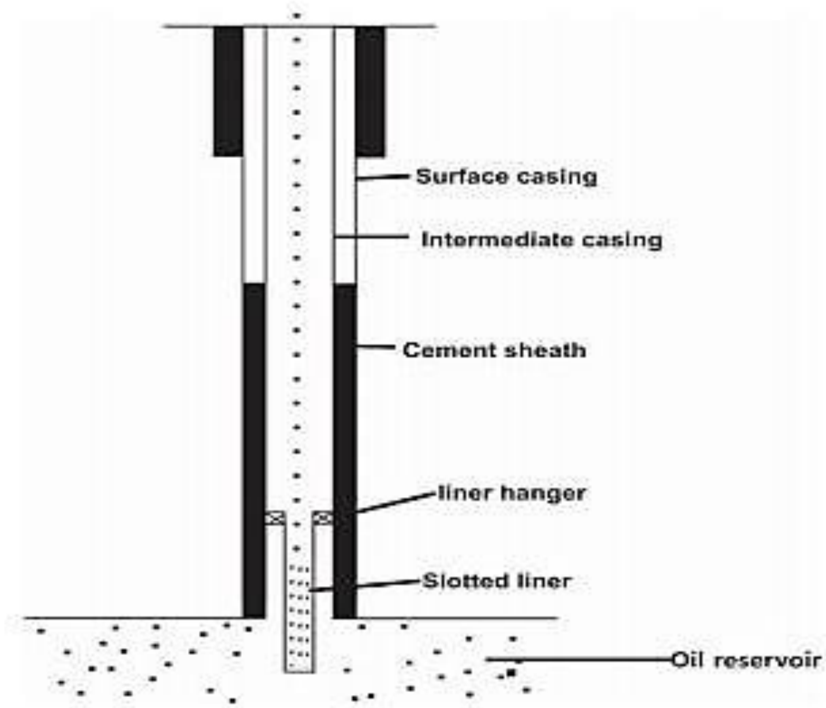

Figure 3.5 Slotted Liner Completion

iv. Gravel Pack Completion

In wellbores which are drilled in loose formations and can face serious sand production are recommended to place gravel pack completion[9]. Open hole gravel pack completion is placed where there is no gas cap and bottom water and cased hole completion are suited in opposite situations[9]. It is desirable completion for controlling sanding problems and to prevent the collapse of stratum. It has a huge positive impact in well completion technology to handle some serious issues, but its installation job is very complex and expensive[1].

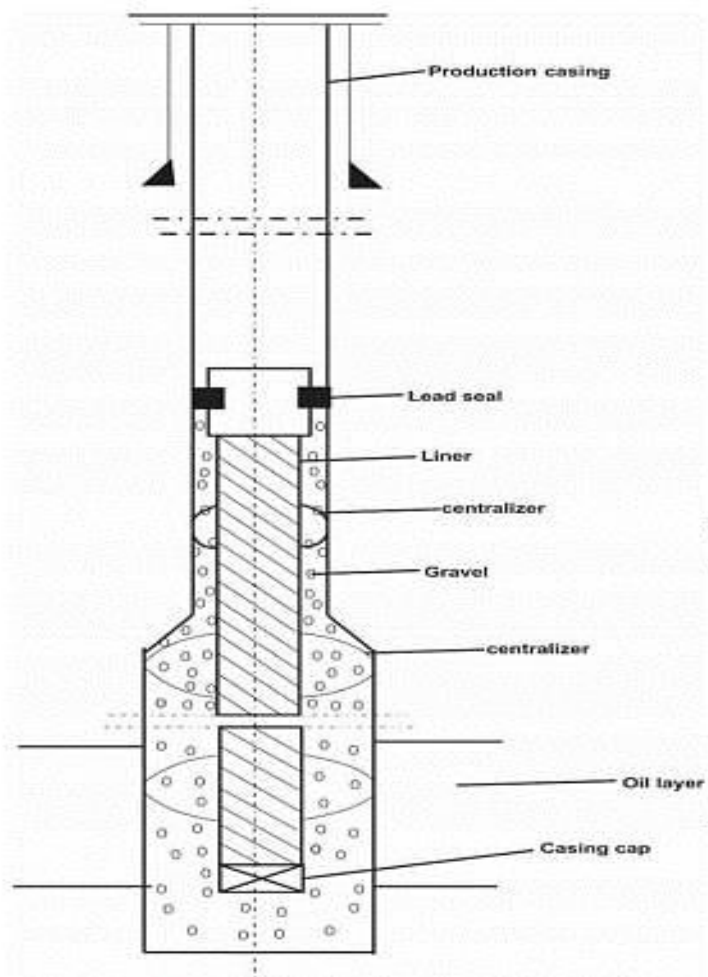

Figure 3.6 Gravel Pack Completion-Open Hole

3.1.2 Well Completion Types for Horizontal Well

i. Expandable Tubular Completion

Slotted liner and expandable sand control screen pipe are two major components of expandable tubular completion[9]. It reduces the flow resistance because the distance between the liner and formation wall is quite low, so in this way it provides wider area. It is useful completion techniques for deviated wells. Chances of collapse of wellbore walls are low and sand control screen have prolonged life in this completion[57]. There are few challenges in this type of completion as there is always possibility of sticking completion in reservoir, so it poses major issue if it gets stuck in wellbore due its low tensile strength[57].

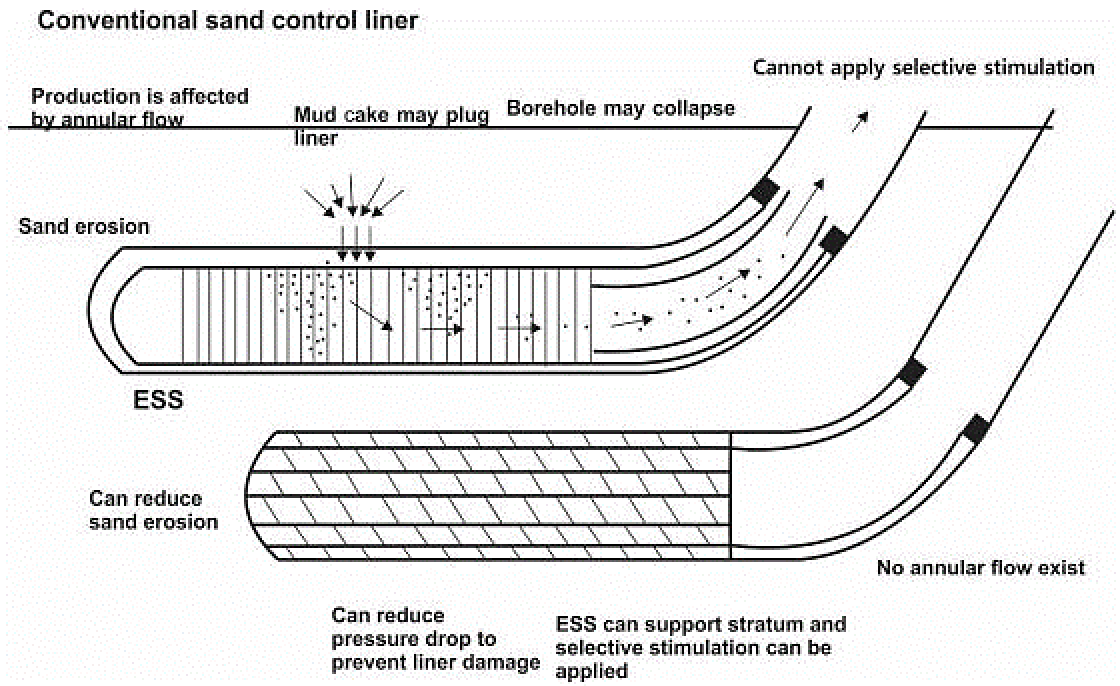

Figure 3.7 Expandable Tubular Well Completion

ii. External Casing Packer Completion

ECP completions[9] are inserted in different layers to successfully carry out the post-drilling operations and to control the production in these layers. It is not expensive as compared to the cased hole completion and also ECP reduces the inter connection between stratum layers. It is possible to apply the stimulation in different layers separately. However, to isolate the strata is quite challenging job which depends on various factors e.g. wellbore shape. The assurance of this method to isolate strata is always hard to predict precisely.

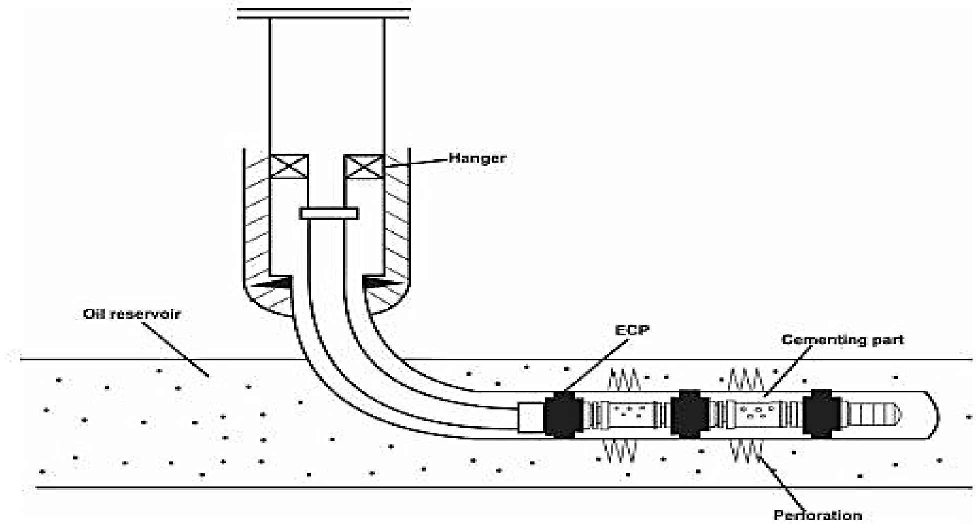

Figure 3.8 External Casing Pack Completion

iii. Open Hole Completion

In horizontal wells open hole completion provide various advantages as it has expandable packers which are useful if there is a need to isolate the layers and production of fluids can be controlled as required. This completion also benefits in terms of production examination as it includes downhole flowmeters[58]. On the flip side, the selective stimulation is not possible. It is not recommended for weak lithology formations[9].

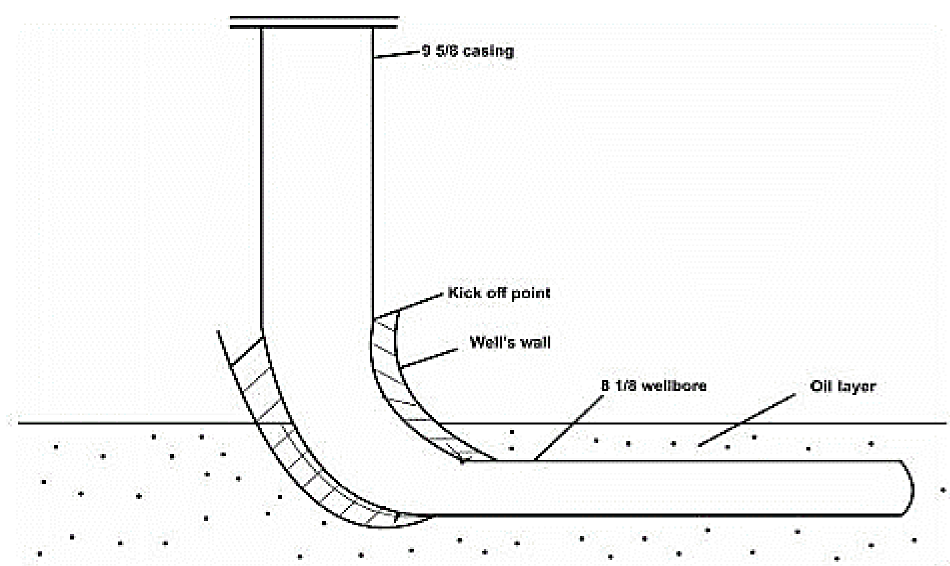

Figure 3.9 Horizontal Wells Open Hole Completion

iv. Slotted Liner Completion

In horizontal well completions, the slotted liner is comparatively less expensive and damage due to mud is not much intense[9]. It provides support to the wellbore to prevent collapse. Small scale stimulation can be done in this type of completion in horizontal wells[9]. Conversely, it is very hard to control the production and also the production data from downhole is impossible to collect for testing[9].

The gravel pack completion and cased hole completion are also used for horizontal well completion.

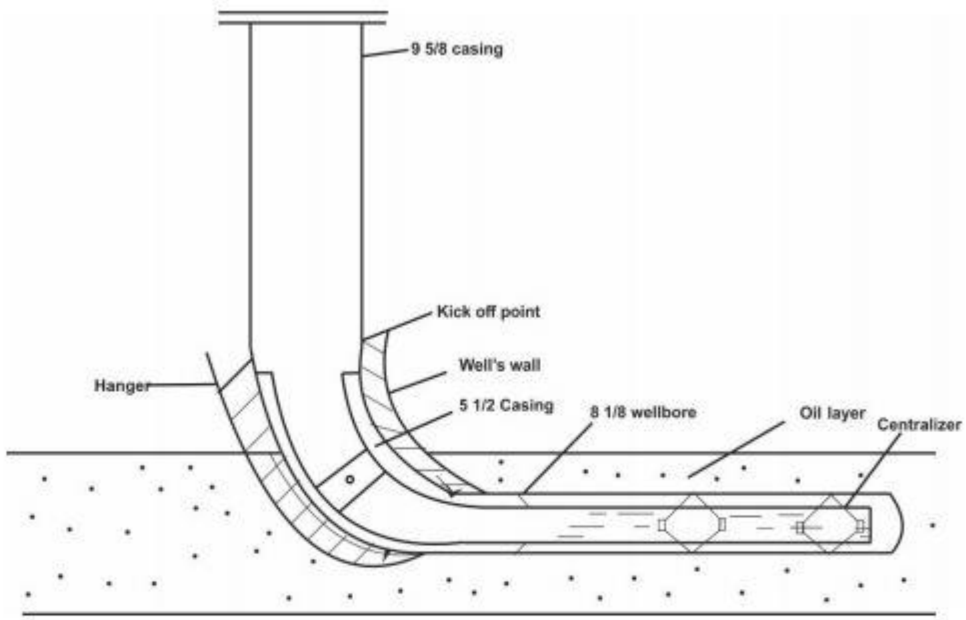

Figure 3.10 Horizontal Well Slotted Liner Completion

4 Chapter 4: Development of Fuzzy TOPSIS Prototype for Well Completion Selection

In this section, the mathematical model, and functions of Fuzzy TOPSIS environment are explained. The backbone of Fuzzy TOPSIS software prototype is discussed to better understand the methodology of this system. These mathematical models which runs all the function in the software prototype are working to solve the decision-making problems in industry. Fuzzy TOPSIS environment is then applied to case studies to select the well completion system for a given formation.

4.1 Overview of Fuzzy TOPSIS Chen's Method

The technique for order of preference by similarity to ideal solution (TOPSIS) is used in decision making problems to get better insight of weight of all criterions for a given problem and number of alternatives are ranked based on the expert's judgement. In TOPSIS, it easier to handle the data for computation purposes and it can adjust both qualitative and quantitative analysis in it. To make decision in real-life the crisp data is not accurate enough to give any optimized solution due inaccuracy and missing values in the provided data[59]. In this research the Chen's 2000 method is used for decision making. A classical Fuzzy TOPSIS method which is also knows as Chen's method is a first extension of Fuzzy TOPSIS method proposed in 2000. In this thesis, the linguistic variables are used to avoid those inaccuracies in the data, and linguistic variables assign weight and preference to each criterion and alternative[59]. To solve the decision-making problem in fuzzy environment where we deal with multi-person and multi-criteria the TOPSIS technique will further be developed for that kind of problems. After assigning the linguistic variables to both criteria and alternative and once experts have proposed the fuzzy ratings, the next step is to convert the decision matrix in the fuzzy decision matrix, which will then be a weighted normalized fuzzy matrix. After these initial steps, according to TOPSIS, the fuzzy ideal positive solution (FPIS) and fuzzy ideal negative solution (FNIS) are determined. Vertex technique is applied at this stage to figure out the distance of alternatives from FPIS and FNIS[59]. Closeness coefficient ranks the given set of alternatives for each criterion, and the alternative on top of the ranking indicates it closeness to the fuzzy positive ideal solution[59]. In the next section, the basic mathematical model and notation of fuzzy number are discussed.

4.1.1 Fuzzy Set Definition and Mathematical Equations

Fuzzy set basic mathematical expressions and definitions are shown below[59]:

a. Membership function $\mu_{\tilde{A}}(x)$ denotes the fuzzy set $\tilde{A}$. X is universe discourse for $\tilde{A}$. The membership grade of x in $\tilde{A}$ is the function value of $\mu_{\tilde{A}}(x)$.

b. The expression given below shows the convex nature of fuzzy set $\tilde{A}$:

$$\mu_{\tilde{A}}(\lambda x_1 + (1-\lambda)x_2) \geqslant \text{Min}\left(\mu_{\tilde{A}}(x_1), \mu_{\tilde{A}}(x_2)\right)$$
$$\text{where } \lambda \in [0,1]$$

c. A fuzzy set $\tilde{A}$ is considered as a normalized when it satisfies this:

$$\exists x_i \in X, \mu_{\tilde{A}}(x_i) = 1$$

d. Fuzzy subset contains the fuzzy number in the universe of discourse X. Normal and convex nature of fuzzy subset is shown below in Fig 4.1:

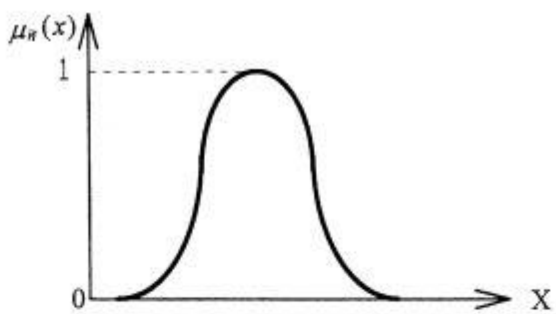

Figure 4.1 Fuzzy Number [59]

e. The Fig 4.2 below and expression defines the fuzzy numbers α-cut:

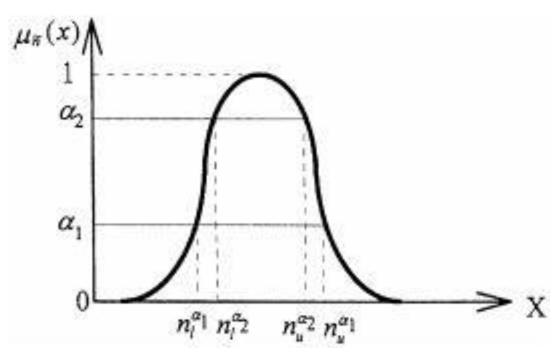

Figure 4.2 Alpha cut of Fuzzy number [59]

f. $(n_1 n_2 n_3)$ as a triplet defines the triangular fuzzy number $\tilde{n}$. The membership function of triangular fuzzy number is as follow:

$$\mu_{\tilde{n}}(x) = \begin{cases} 0, & x < n_1, \\ \frac{x-n_1}{n_2-n_1}, & n_1 \leqslant x \leqslant n_2 \\ \frac{x-n_3}{n_2-n_3}, & n_2 \leqslant x \leqslant n_3 \\ 0, & x > n_3. \end{cases}$$

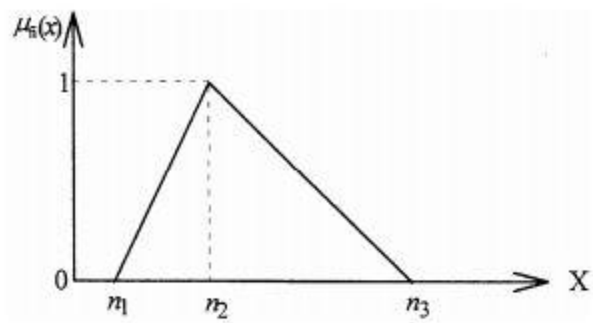

Figure 4.3 Triangular Fuzzy Number [59]

g. Where $n_l^\alpha > 0$ and $\alpha \in [0\ 1]$ the fuzzy number is called as positive fuzzy number. The equations below show the basic operations of positive fuzzy numbers $\widetilde{m}$ and $\tilde{n}$:

$$(\widetilde{m}(+)\tilde{n})^\alpha = [m_\ell^\alpha + n_l^\alpha, m_{\mathrm{u}}^\alpha + n_{\mathrm{u}}^\alpha],$$
$$(\widetilde{m}(-)\tilde{n})^\alpha = [m_\ell^\alpha - n_{\mathrm{u}}^\alpha, m_{\mathrm{u}}^\alpha - n_\ell^\alpha],$$
$$(\widetilde{m}(\cdot)\tilde{n})^\alpha = [m_\ell^\alpha \cdot n_\ell^\alpha, m_{\mathrm{u}}^\alpha \cdot n_{\mathrm{u}}^\alpha]$$
$$(\widetilde{m}(:)\tilde{n})^\alpha = \left[\frac{m_l^\alpha}{n_{\mathrm{u}}^\alpha}, \frac{m_{\mathrm{u}}^\alpha}{n_\ell^\alpha}\right],$$
$$(\widetilde{m}^\alpha)^{-1} = \left[\frac{1}{m_{\mathrm{u}}^\alpha}, \frac{1}{m_\ell^\alpha}\right],$$
$$(\widetilde{m}(\cdot)r)^\alpha = [m_\ell^\alpha \cdot r, m_{\mathrm{u}}^\alpha \cdot r]$$
$$(\widetilde{m}(:)r)^\alpha = \left[\frac{m_\ell^\alpha}{r}, \frac{m_{\mathrm{u}}^\alpha}{r}\right].$$

h. When this situation, $n_\ell^\alpha > 0, n_{\mathrm{u}}^\alpha \leqslant 1$ for $\alpha \in [0,1]$ satisfies, a triangular fuzzy number is a normalized positive triangular fuzzy number.

i. A fuzzy matrix is indicated by $\widetilde{D}$.

j. Linguistic variable values are depicted in linguistic terms. In calculation process, the linguistic variables are converted to fuzzy numbers.

k. In Fuzzy TOPSIS vertex method measures the distance between two triangular fuzzy numbers $\tilde{m}$ and $\tilde{n}$ as defined below:

$$d(\tilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2]}$$

4.1.2 Fuzzy TOPSIS: Development of Proposed Methodology in Decision Making

In this part, the stepwise approach to build the fuzzy environment from TOPSIS is explained. As we clearly understand that the well completion selection is multi-disciplinary task and it has to handle the opinions of experts from various discipline involving multiple criteria and alternatives to be considered in decision making. Group decision making scenarios are dealt in a very systematic approach under fuzzy environment. The fuzzy environment mathematic and linguistic models are elaborated in this section and it will be the backbone of making decisions for our well completion selection procedure. The Fuzzy TOPSIS software prototype will utilize these models in background to select criteria and alternative for ranking the best possible solution for given problem.

I. Linguistic Variables

In Fuzzy TOPSIS problems linguistic variables are used to minimize the error in human judgments in case of large amount of data as it is hard to come up with exact preferences with exact precision. So numerical values are not a good source of ranking preferences as there is a huge chance of error due to inability of handling huge data sets by experts when making decisions. Pairwise comparison, either directly or indirectly, is one of the techniques to assign the weight to each criterion[60]. In this model, the linguistic variables are used by experts to gauge the importance of all criteria and then assign ratings to each alternative with respect to given set of criterions. The Table 4.1 and 4.2 shows the linguistic variables used in this proposed model:

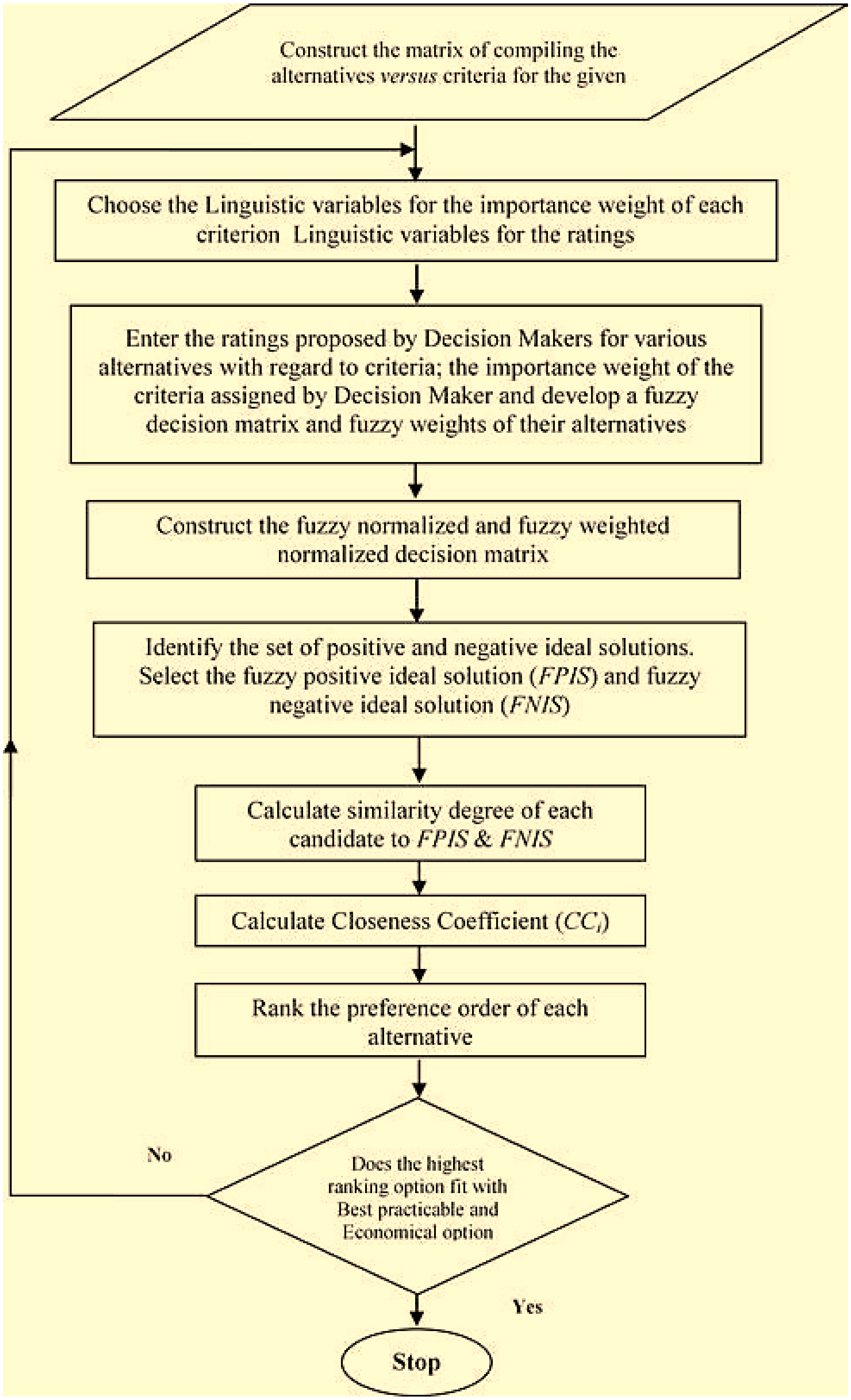

Figure 4.4 Flow Chart of Fuzzy TOPSIS

Table 4.1 Importance weight of criteria by linguistic variables

Very Low (VL)	(0,0,0.1)
Low (L)	(0,0.1,0.3)
Medium Low (ML)	(0.1,0.3,0.5)
Medium (M)	(0.3,0.5,0.7)
Medium High (MH)	(0.5,0.7,0.9)
High (H)	(0.7,0.9,1)
Very High (VH)	(0.9,1,1)

Table 4.2 Alternative rating by linguistic variable

Very Poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium Poor (MP)	(1,3,5)
Fair (F)	(3,5,7)
Medium Good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very Good (VG)	(9,10,10)

II. Weight and Importance of K^{th} Decision Maker

After assigning the linguistic variables to all the criteria and alternatives by decision making group, the number of expert's, which is denoted by K are included to perform the calculation of alternative's rating and criterion importance by following formulas[59]:

$$\tilde{x}_{ij} = \frac{1}{K}\left[\tilde{x}_{ij}^{1}(+)\tilde{x}_{ij}^{2}(+)\cdots(+)\tilde{x}_{ij}^{K}\right] \quad 1$$

$$\tilde{w}_{j} = \frac{1}{K}\left[\tilde{w}_{j}^{1}(+)\tilde{w}_{j}^{2}(+)\cdots(+)\tilde{w}_{j}^{K}\right] \quad 2$$

III. Decision Matrix $\widetilde{D}$

The decision matrix expressed below shows the matrix of multi-person multi-criteria decision problem:

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{11} & \dots & \tilde{x}_{11} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}, \quad 3$$

$$\widetilde{W} = [\tilde{w}_1, \tilde{w}_2, \dots, \bar{w}_n]$$

By using this decision matrix, it is feasible to express the linguistic variables by numerical values or more specifically in terms of triangular fuzzy number. $\tilde{x}_{ij}$ and $\tilde{w}_j$ are linguistic variables[59].

IV. Normalized Fuzzy Decision Matrix $\widetilde{R}$

In the fuzzy environment, it is recommended to perform linear scale transformation rather than complicated normalization process which is usually performed in the classical TOPSIS[59]. We obtain the normalized fuzzy decision matrix by linear scale transformation which helps to generate comparable scale for criterion scale[59]. The following is the formula for normalized decision matrix $\widetilde{R}$:

$$\widetilde{R} = \left[\tilde{r}_{ij}\right]_{m\times n} \quad 4$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B;$$
$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C;$$
$$c_j^* = \max_i c_{ij} \text{ if } j \in B;$$
$$a_j^- = \min_i a_{ij} \text{ if } j \in C.$$

B and C represents the benefit and cost criteria sets.

V. Weighted Normalized Fuzzy Decision Matrix

As the importance of each criteria has different weightage based on the experts' input, so it's an important to build up the weighted matrix for all criterions form normalized fuzzy matrix. The Equation 5 shows the weighted normalized fuzzy decision matrix:

$$\boldsymbol{\widetilde{V}} = \left[\boldsymbol{\tilde{v}_{ij}}\right]_{\boldsymbol{m \times n}} \boldsymbol{i = 1, 2, \ldots, m, j = 1, 2, \ldots, n,} \tag{5}$$

where $\boldsymbol{\tilde{v}_{ij}} = \boldsymbol{\tilde{r}_{ij}}(\cdot)\boldsymbol{\widetilde{w}_j}$

VI. Fuzzy Positive Ideal Solution A^* and Fuzzy Negative Ideal Solution A^-

We know that $\boldsymbol{\tilde{v}_{ij}}$, $\forall i$, and *j* are normalized positive triangular fuzzy numbers as stated by weighted normalized fuzzy decision matrix, and the interval [0, 1] is the range of normalized positive triangular fuzzy number[59]. So now we can define the FPIS and FNIS to proceed further in the calculation process by following expressions:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*)$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-)$$

Where $\tilde{v}_j^* = (1,1,1)$ and $\tilde{v}_j^- = (0,0,0)$, *j*=1,2, n.

VII. Distance Calculation

The next step after determining the FPIS and FNIS, the distance of all the alternatives, presented to solve the given decision-making problem, is computed as below[59]:

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), i = 1, 2, \dots, m \quad (6)$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), i = 1, 2, \dots, m \quad (7)$$

Fuzzy numbers' distance is showed by these expressions. The closer is the alternative to the positive ideal solution, the lesser the distance it will have, and it is more distance for alternatives with which are not/less suitable to apply to solve a given problems.

VIII. Closeness Coefficient

Once we have performed the distance calculations of all the alternatives A_i $i = 1,2,3$, the next step is to determine the closeness coefficient of each alternative, so it is easier for decision makers to evaluate the ranking of alternative and choose the best alternative[59]. The closeness coefficient actually creates a ranking order for the alternative A_i.

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-}, i = 1, 2, \dots, m \quad (8)$$

As CC_i value is closer to 1, it indicates that the alternative A_i is nearest to the fuzzy positive ideal solution. The most appropriate alternative is then available in final ranking order system after evaluation with each criterion.

4.1.3 Synopsis of Fuzzy TOPSIS Algorithm

The step by step procedure to follow the Fuzzy TOPSIS algorithm to solve the decision-making problems with fuzzy set involving multi-criteria and multi-expert is summarized below:

1st. Structure an advisory group of decision-makers, at that point recognize the assessment criteria.

2nd. Pick up proper linguistic variables and linguistic listings for the importance weight of criteria as well as for alternatives regarding each criterion.

3rd. The collected fuzzy weight $\tilde{w}_j$ for each criterion C_j is calculated by aggregating the criterion weight, and the aggregated fuzzy ratings $\tilde{x}_{ij}$ of all the alternatives A_i under each criterion in a given problem is determined by combining the expert's decisions.

4th. In the fourth step we develop the fuzzy decision matrix and after that it is normalized to construct a normalized fuzzy decision matrix.

5th. In this step the previously constructed matrix is converted to weighted normalized fuzzy decision matrix.

6th. Calculation of fuzzy positive ideal solution and fuzzy negative ideal solution is performed in this step.

7th. Given alternatives distance from FPIS and FNIS is calculated.

8th. Once the distance is determined, we proceed with to find the closeness coefficient.

9th. Ranking order is calculated for all alternatives on the authority of closeness coefficient.

4.2 Fuzzy TOPSIS Algorithm Numerical Example

In this section, a sample of decision-making problem will be discussed to perform the Fuzzy TOPSIS software to understand the its workflow. The use of Fuzzy TOPSIS software will be elaborated with all the steps involved in it. The purpose of this software prototype is to make the complex calculation procedure simple and steady, and mostly it requires simple inputs to solve the given problem. This software prototype is able to select the optimized well completion models for any specific formation. In the next chapter, the real-time case studies to select the optimum well completion will be dealt by using the Fuzzy TOPSIS software, but in this section only sample example is used to explain it.

Assume that oil and gas operator company hire a team of experts from various disciplines to select the suitable well completion design to install in the wellbore. Let suppose we have three alternatives of well completions A_1, A_2, and A_3 for ranking and then select the one based on ranking and criteria weight. The decision-making team has three experts, D_1, D_2, D_3 to weight and rate each criterion and alternative. The decision-making team has defined three criteria C_1, C_2, and C_3 to evaluate the given alternative options for well completion selection.

Suppose the three criteria are:

i. Production (C_1)

ii. Cost (C_2)

iii. HSE

The above given criteria are used as an example to select the appropriate alternative and it is not real-life example. Although for actual problems it follows the same rule to develop the decision-making process for evaluation purposes.

In the Fuzzy TOPSIS software, it has an option to select either the criteria are positive (beneficial) or negative (disadvantageous). In input values, we assign +1 for positive criteria and -1 for negative criteria. In our defined criteria, it is supposed that production of wellbore and HSE are positive criteria, and the cost of well completion activities is assumed as negative criteria. So, until now we have defined the alternatives, number of experts, type and number of criteria.

Step 1: In the first step, the experts will weigh the importance of each criteria. For the importance weight of each criteria the decision maker will use the linguistic variable Table 4.1.

Table 4.3 The importance weight of criteria by experts

	D_1	D_2	D_3
C_1	VH	H	VH
C_2	ML	L	M
C_3	H	VH	MH

In the Table 4.3, the experts have given their input to weight each criterion by using the linguistic variables which makes it less tedious task for the team of experts in their domain to do that task. In the Fuzzy TOPSIS software the following inputs are given.

Table 4.4 Insert the number of experts in Fuzzy TOPSIS Software

Experts	3

Table 4.5 Insert the number of criteria

Criteria	3

Table 4.5 Insert the number of alternatives

Alternative	3

Table 4.6 Type of criteria

	Positive	Negative
Criteria type	+1	-1

Step 2: So, until now it is pretty simple inputs to insert in the Fuzzy TOPSIS program. Next, in Table 4.7, the criteria weight is inserted based on the linguistic variables assigned to the three criteria by experts in Table 4.3.

Table 4.7 Assigning weight to each criterion

Criteria	Type	Weight
C_1	+1	0.83
		0.96
		1

Criteria	Type	Weight
		0.13

C_2	-1	0.3
		0.5

Criteria	Type	Weight
		0.7
C_2	+1	0.86
		0.96

In Table 4.7, the criteria weight, and the type of each criteria have been set up in the programs.

Step 2: So far, we have established the all the important inputs in the Fuzzy TOPSIS program, and now the further step is very simple but after its various complex calculation are initiated in the system to obtain the fuzzy decision matrix, normalized and weighted normalized fuzzy decision matrix. They are so simple, as it is shown in Table 4.8, where we assign the number of experts to each alternative by using the linguistic variables to get the alternative ranking. All the alternative ratings (A_1, A_2, A_3) under the given criteria C_1, C_2, and C_3 are presented below:

Table 4.8 Alternative showing number of experts in their favor w.r.t to linguistic variables

	C_1						
	VP	P	MP	F	MG	G	VG
A_1				1	1	1	
A_2				1	2		
A_3						2	1

C_2							
	VP	P	MP	F	MG	G	VG
A_1				1	2	1	
A_2				2		1	
A_3			1	1	1		

C_3							
	VP	P	MP	F	MG	G	VG
A_1			1		1	1	
A_2				1	1		1
A_3					1	2	

All the numerical values given to the alternatives under each criterion show the number of experts and the linguistic variables column shows how many experts are how much in favor of any individual alternative. For example, for the criteria C_1 two experts say that the alternative A_3 is good (G) and one expert say it is very good (VG) option.

Step 3: Equation 3, equation 4, and equation 5 have been set up in the Fuzzy TOPSIS program to calculate integrated, normalized, and weighted fuzzy decision matrix. After the step 2, the program will get the data from the previous steps to perform its function.

Step 4: In this stage, the software defines the FPSI and FNIS for all the criterion, which is a primary step to go to the next step where the program calculates the distance of each alternative.

Table 4.9 Defining FPIS and FNIS inputs for criteria

	C_1		
A^*	1	1	1
A^-	0	0	0

	C_2		
A^*	1	1	1
A^-	0	0	0

	C_3		
A^*	1	1	1
A^-	0	0	0

Step 5: Now the program starts off to calculate the distance of each alternative, for all criterion, from A^* and A^-using the equation 6 and equation 7. The following table 4.10 shows the calculations performed in the program.

Table 4.10 Distance calculation of alternatives from FPIS and FNIS

	C_1	C_2	C_3	d_i^*
A_1	0.395	0.831	0.484	1.710
A_2	0.444	0.830	0.430	1.677
A_3	0.218	0.778	0.347	1.343

	C_1	C_2	C_3	d_i^-
A_1	0.677	0.218	0.591	1.485
A_2	0.631	0.218	0.667	1.515
A_3	0.858	0.308	0.749	1.915

Finally, this step has completed the distance calculation of all alternative. Here, the vertex method calculated the distance between two fuzzy numbers. The alternative which is nearest to the FPIS or have more positive distance can be considered as the suitable alternative to choose among the given options.

Step 6: In the last step, the program uses the algorithm to perform the closeness coefficient calculations, according to Equation 8, to finally give the ranking order of all the alternative so it becomes easier for decision-makers to analyze the final output and choose the best alternative under the given criterion.

Table 4.11 Ranking order of alternatives

		Ranking of Alternative	
A_1	0.46		3
A_2	0.47		2
A_3	0.58		1

The Table 4.11 show that the alternative A_3 is the best well completion method to select after considering the production, cost and HSE criteria, and taking account of the experts' opinion. As it was explained earlier this is not a real-life problem, it is only demonstrated here to show the stepwise working mechanism of the Fuzzy TOPSIS program.

5 Chapter 5: Case Study for Well Completion Model Selection for Iris Production Well by Fuzzy TOPSIS Algorithm

In this case study[61], the Fuzzy TOPSIS system is implemented on the Iris production well. It is a real-time example to use the decision-making process for optimized selection of well completion design. Iris field is situated on the North Continental Shelf and to the west of Morvin Field. Iris reservoir is found around 225m under the Hades reservoir. Iris reservoir properties evaluation indicates that it belongs to Garn Formation of Middle Jurassic age. Iris appraisal well 6506/11-11S was drilled in 2019 to investigate the potential of Iris reservoir and to get in-depth knowledge and properties of its depositional model. Reservoir characteristics, conditions, and the Iris Appraisal well design will be considered for assessment for the Iris production well design. Morvin Field is HPHT field and has some similarities to Iris field, for example same temperature and pressure, 162 degree C and 819 bar, as Iris field, so Morvin field can be considered as reference during the selection procedure of completion design for Iris production well.

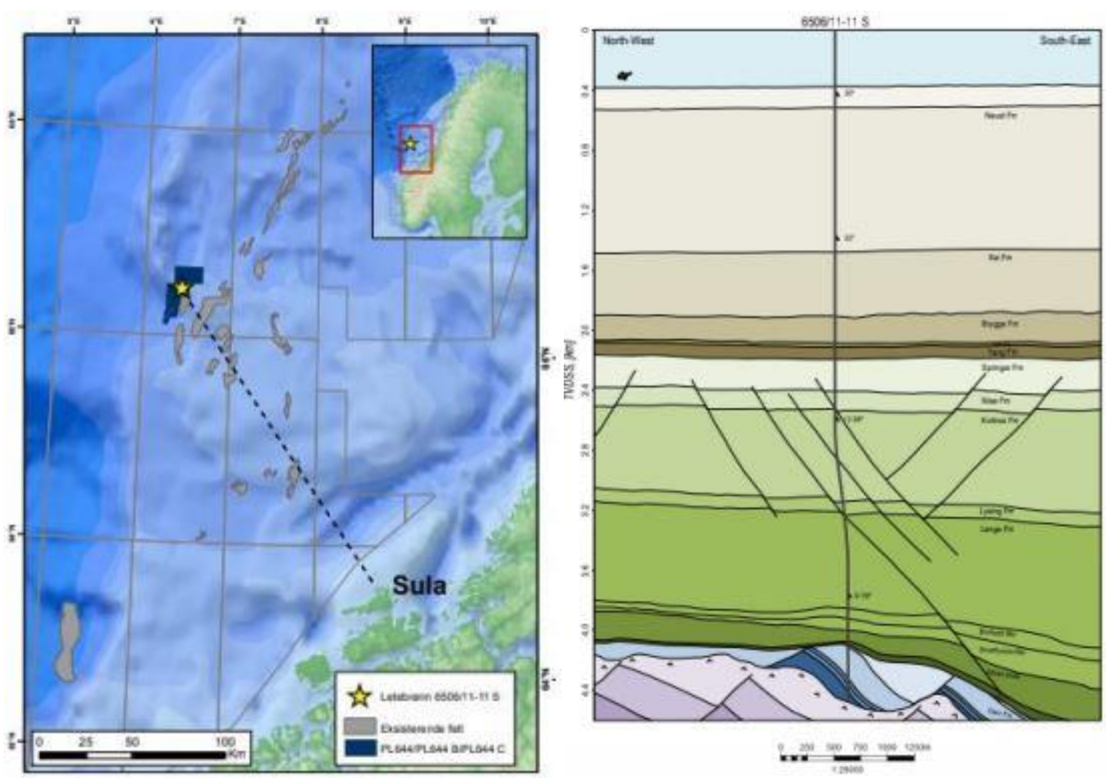

Figure 5.1 Iris Field Well Location and Well Trajectory[61]

5.1 Criteria Selection for the Iris Production Well

The experts involved during the well completion selection process for decision-making have to consider and drive the criteria which have more values for various objectives to achieve. The value of the chosen criterion may vary depending upon the involvement of operations for certain field. Based on this the criterion are given weight and prioritized by expert knowledge. HS&E is an utmost important criterion for well completion team as the environmental management, safety and health of technical crew can never be compromised. Both operator and service companies recommend their safety procedures, tool/equipment selection, and consequences of environmental challenges in the long run, and their endorsement need to take very seriously and prioritized. Well objective is another value-driven criterion during well completion selection task, as it helps to derive the production potential for the selected completion method. Well objective criteria also assess the operational safety in case of performance variation of the well. The next consideration for the criteria is time and cost which is important factor for companies in economic point of view. Time and cost criteria assist to evaluate the cost estimation of various well completion activities, well intervention and equipment selection for HPHT wells. So, HS&E, well objective, and time and cost are the three criterion we will consider for completion selection.

- **HS&E**
  - Well integrity should always be maintained. Potential risk to the well integrity includes corrosion of the downhole equipment, leak of gas, weak zonal isolation, and pressure buildup in annular.
  - Detrimental impact to the environment and human safety can't be trad-off.
  - Well performance must be taken into consideration while making HS&E regulation.
  - HS&E standards should be of high value in well completion design.

- **Well Objectives**
  - Recovery of hydrocarbons from reservoir should be improved.
  - High focus on well integrity.

- Compatible design for well intervention activities.
- Well objective must include the plug and abandonment activities.
- Design needs to get optimized production.
- Meet the complex conditions for HPHT wells.

- **Time and Cost**
  - Rig-time for various operational activities is a major factor to manage the economic value of the field.
  - All activities should be planned properly to save time and cost.
  - Optimization of various completion equipment and the rig-rate is a strategy for cost-effective well coemption activities.

The following Table 5.1 shows the importance weight of each criteria for Iris production well, the criteria to each weight is given by the team of decision-making experts.

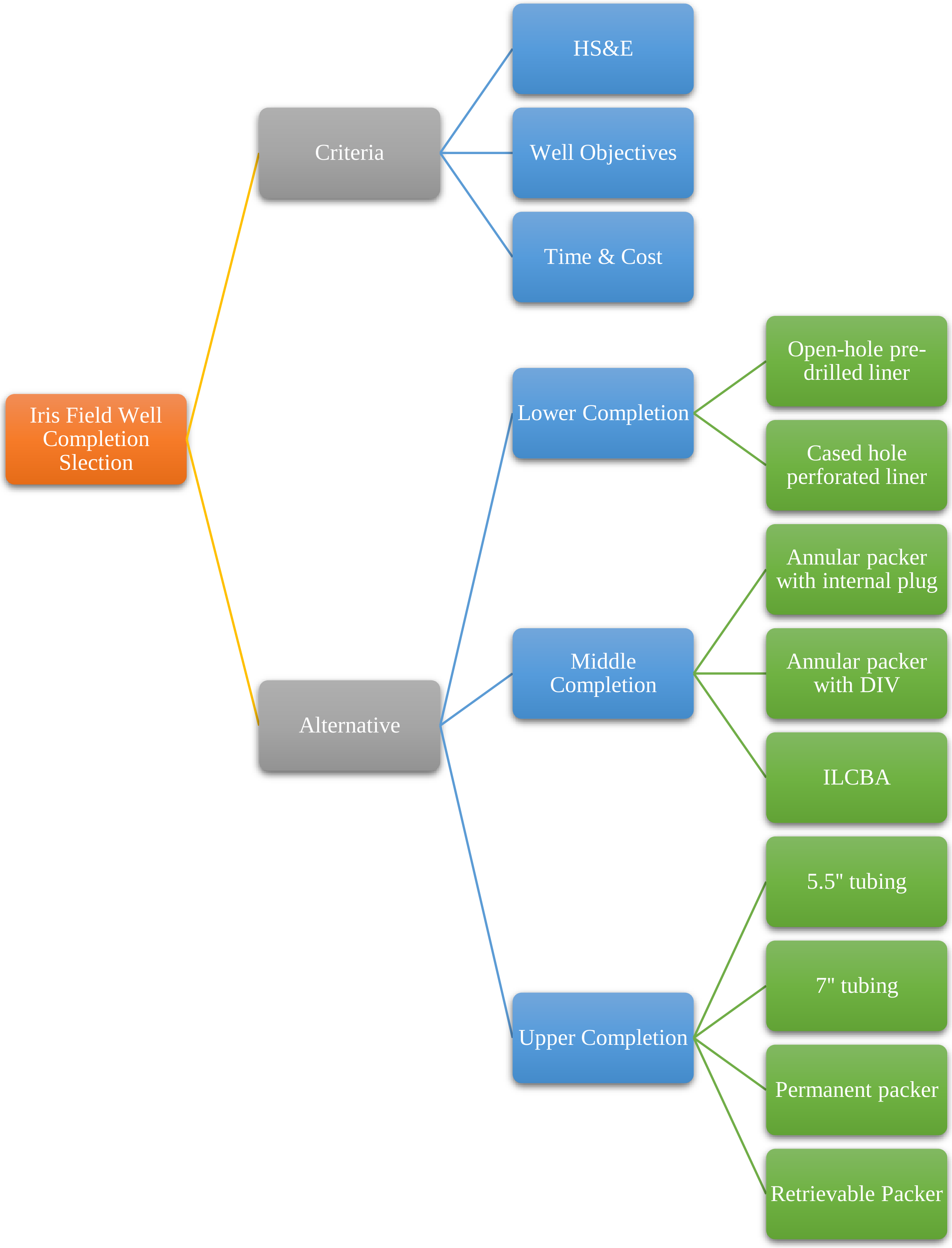

Figure 5.2 Flow chart for criteria and alternative for Iris Production Field

Table 5.1 Iris Production Well criteria weight importance

Criteria	Symbol	Type	Linguistic Variable / Importance	Weight
HS&E	C_1	+1	Very High (VH)	(0.9,1,1)
Well Objective	C_2	+1	High (H)	(0.7,0.9,1)
Time & Cost	C_3	-1	Medium High (MH)	(0.5,0.7,0.9)

So, the setup to perform the Fuzzy TOPSIS program for optimized well completion selection for the Iris production well have been initiated. The three criterions C_1, C_2, C_3 have been chosen and a team of four decision-experts D_1, D_2, D_3, D_4 have given the weight to each criterion shown in the Table 5.1.

For the optimized well completion method selection for Iris production field, it is decided to consider the lower completion, middle completion, and upper completion separately under the given criterion. In this Fuzzy TOPSIS software, the alternative ranking order will be assessed for lower, middle, and upper completions. The ranking order of alternative will be determined separately for all three completions. We will consider the relevant alternatives for lower, middle, and upper well completions.

The alternative for each completion is given below:

Lower Completion:

- Open hole pre-drilled liner A_1
- Cased hole perforated liner A_2

Factors to be considered for lower completion selection:

- Perforation quality

- ➢ Well instability
- ➢ Formation damage
- ➢ Tool malfunction
- ➢ Zonal isolation

Middle Completion:

- – Annular packer with Internal plug A_1
- – Annular packer with downhole isolation valve A_2
- – Integrated lower completion barrier assembly (ILCBA) A_3

Factors to be considered for middle completion selection:

- ➢ Failure to access internal plug and valve
- ➢ Surge and Swab effect
- ➢ ID restrictions

Upper Completion:

1. **Casing**
    - – 5 1/2-inch tubing A_1
    - – 7-inch tubing A_2
2. **Packer**
    - – Permanent packer A_1
    - – Retrievable packer A_2

Factors to be considered for upper completion:

- ➢ Historical reliability
- ➢ Subsea equipment restriction
- ➢ ID clearance

- Packer reliability in HPHT
- Historical fact to use packer in NCS

5.1.1 Lower Completion Selection Using Fuzzy TOPSIS

As there are two major completions, open hole pre-drilled and cased hole perforated liner to choose for Iris production well. These two alternatives will be assessed under three criteria HS&E, well objective, time & cost. In this method, each factor will be considered for rating of alternative and based on the ranking order the software will decide the one alternative either open hole pre-drilled liner or cased hole perforated liner.

Table 5.2 Rating of alternative for lower completion by experts

	HS&E (C_1)						
	VP	P	MP	F	MG	G	VG
Open hole pre-drilled liner (A_1)	-	-	-	-	1	1	2
Cased hole perforated liner (A_2)	-	-	-	-	2	2	-

	Well Objective (C_2)						
	VP	P	MP	F	MG	G	VG
Open hole pre-drilled liner (A_1)	-	-	-	-	-	2	2

Cased hole perforated liner (A_2)	-	-	-	1	2	1	-

	Time & Cost (C_3)						
	VP	P	MP	F	MG	G	VG
Open hole pre-drilled liner (A_1)	-	-	-	1	2	1	-
Cased hole perforated liner (A_2)	-	-	2	1	1	-	-

Table 5.3 Ranking Order of alternatives for lower completion

		Ranking of Alternative	
A_1	0.63		1
A_2	0.60		2

In terms of time & cost criteria open-hole pre-drilled liner consumes less time and are more cost-effective as it is obvious the well completion teams have to perform more operation for cased hole liner e.g. to insert the liner, run cement, test the cement bond etc. One important factor to consider is that the loss of drilling fluids into reservoirs cause the filtrate formation in open-hole pre-drilled liner which not the case for cased hole perforated liner. The chances of malfunction of release tool in the wellbore, and minimum gun shocks (for perforation) keeps the wellbore stability and it provides decision-makers more reliability to select the open-hole pre-drilled liner.

5.1.2 Middle Completion Selection Using Fuzzy TOPSIS

For middle completion selection, three alternatives will be considered for further evaluation under each criterion and all factors will be taken into account by experts while rating the alternatives. ILCBA, annular packer with plug, and annular packer with isolation valve are three alternatives for middle completion. Middle completion is run into the well as part of the lower completion. As mentioned earlier, the failure to reach to the internal plug, swab/surge affect, and ID restrictions are some of the important factors to be considered for experts while rating the alternatives.

In Table 5.4, the Fuzzy TOPSIS is implemented on the three alternatives for middle completion selection. The experts will give their input using the linguistic variables presented in the Table 4.2 for alternative ratings.

Table 5.4 Rating of alternatives for middle completion

	HS&E (C_1)						
	VP	P	MP	F	MG	G	VG
Annular Packer with internal valve (A_1)	-	-	-	-	1	3	-
Annular Packer with DIS (A_2)	-	-	-	1	1	2	-
ILCBA (A_3)	-	-	-	-	-	1	3

	Well Objective (C_2)						
	VP	P	MP	F	MG	G	VG
Annular Packer with	-	-	-	1	1	2	-

internal valve (A_1)							
Annular Packer with DIS (A_2)	-	-	-	1	2	1	-
ILCBA (A_3)	-	-	-	1	-	1	2

	Time & Cost (C_3)						
	VP	P	MP	F	MG	G	VG
Annular Packer with internal valve (A_1)	-	-	-	-	2	2	-
Annular Packer with DIS (A_2)	-	-	-	1	2	1	-
ILCBA (A_3)	-	-	-	-	1	1	2

Table 5.5 Ranking order of alternatives

		Ranking of Alternative	
A_1	0.63		2
A_2	0.62		3
A_3	0.67		1

Above Table 5.5 manifest the selection of ILCBA for middle completion solution based on the decision-maker opinion. Although the annular packer middle completions are more reliable, but they can be time consuming and with more probability to face well stability issues as compared to ILCBA. While ILCBA comes up with a solution to eliminate the need for middle completion separately as it runs as part of the lower completion with more advantage in favor of well integrity and also reduced the risk of swab/surge in wellbore.

5.1.3 Upper Completion Selection Using Fuzzy TOPSIS

The selection of upper completion involves the two alternatives for tubing selection, 5-inch tubing and 7-inch tubing, and the permanent and retrievable packer are the other two alternatives to select for packer selection. The Fuzzy TOPSIS will be implemented on these two types of alternative, tubing and packer, separately to obtain the ranking of alternative. Table 5.6 is presented to select the tubing alternative. Table 5.7 shows the final ranking of the given alternatives.

Table 5.6 Ratings of tubing alternative for upper completion

	HS&E (C_1)						
	VP	P	MP	F	MG	G	VG
5-inch tubing (A_1)	-	-	-	-	-	2	2
7-inch tubing (A_2)	-	-	-	1	2	1	-

	Well Objective (C_2)						
	VP	P	MP	F	MG	G	VG
5-inch tubing (A_1)	-	-	-	-	-	1	3
7-inch tubing (A_2)	-	-	-	2	2	-	-

	Time & Cost (C_3)						
	VP	P	MP	F	MG	G	VG
5-inch tubing (A_1)	-	-	-	-	-	2	2
7-inch tubing (A_2)	-	-	-	1	-	2	1

Table 5.7 Ranking order of alternatives

		Ranking of Alternative	
A_1	0.71		1
A_2	0.58		2

The 5-inch tubing has attained more attention of the decision-makers as 5-inch tubing has provided successful completion activities on NCS for subsea wells. Historically, it has been noted that 7-inch tubing can cause hurdle in operations on subsea platform. For example, the restriction of tools when running the equipment into the wellbore. While on the other hand the 5-inch tubing is knows for causing less problems and disturbance to equipment. When experts compare the ID clearance for both 5-inch and 7-inch tubing, it comes into the notice that 5-inch tubing provides more ID clearance which is very important in terms of running the control lines, pressure and temperature gauges into the wellbore. Based on these factors' experts have given more importance to the 5-inch tubing for the upper completion of Iris production well.

Among the given options for permanent and retrievable packers, the former is field proven on NCS, less complex and easy to install and provides more resilience during field operations. The experts believe that permanent packer has a history to be used on the NCS and mostly the upper completions have been completed with permanent packer. In the Table 5.8, we will assess the comparison of these two types of packer to finally decide which one is better for upper completion model.

Table 5.8 Rating of packer alternatives for upper completion

	HS&E (C_1)						
	VP	P	MP	F	MG	G	VG
Permanent packer (A_1)	-	-	-	-	-	1	3
Retrievable packer (A_2)	-	-	-	-	1	3	-

	Well Objective (C_2)						
	VP	P	MP	F	MG	G	VG
Permanent packer (A_1)	-	-	-	-	2	2	-
Retrievable packer (A_2)	-	-	-	-	2	2	-

	Time & Cost (C_3)						
	VP	P	MP	F	MG	G	VG
Permanent packer (A_1)					1	3	
Retrievable packer (A_2)					1	3	

Table 5.9 Ranking order of alternative

		Ranking of Alternative	
A_1	0.70		1

A_2	0.67		2

The above Table 5.9 indicates that the permanent packer is the more robust solution for Iris production field. Although it is completely feasible to utilize both permanent and retrievable packers in fields with HPHT conditions.

Final Well Completion Design Proposal for Iris Production Well	
Open hole pre-drilled liner	Lower Completion
ILCBA	Middle Completion
5-inch tubing	Upper Completion
Permanent packer	

The GitHub code for the Fuzzy TOPSIS prototype can accessed from this link: https://github.com/bysarmad/fuzzytopsissoftware/tree/main.

5.2 Sensitivity Analysis

By applying the sensitivity analysis on the well completion design for Iris production well different kind of conditions can be assessed and compared to the original scenario. The quality of a given problem relies on the knowledge and understanding of the mathematical model. Various kind of uncertainties can be related to this model. As the sensitivity analysis is applied on the Fuzzy TOPSIS model, it makes it possible to analyze the variations in output variables which are affected by the uncertainties of input variables. In Fuzzy TOPSIS, the sensitivity analysis can be applied to create different kind of scenarios to examine the alternative ratings (output variable), and these alternative ratings are sensitive enough to get altered by changing any input variable. The input variable in Fuzzy TOPSIS can be the decision maker (DM), criteria weighting, number of alternatives etc.

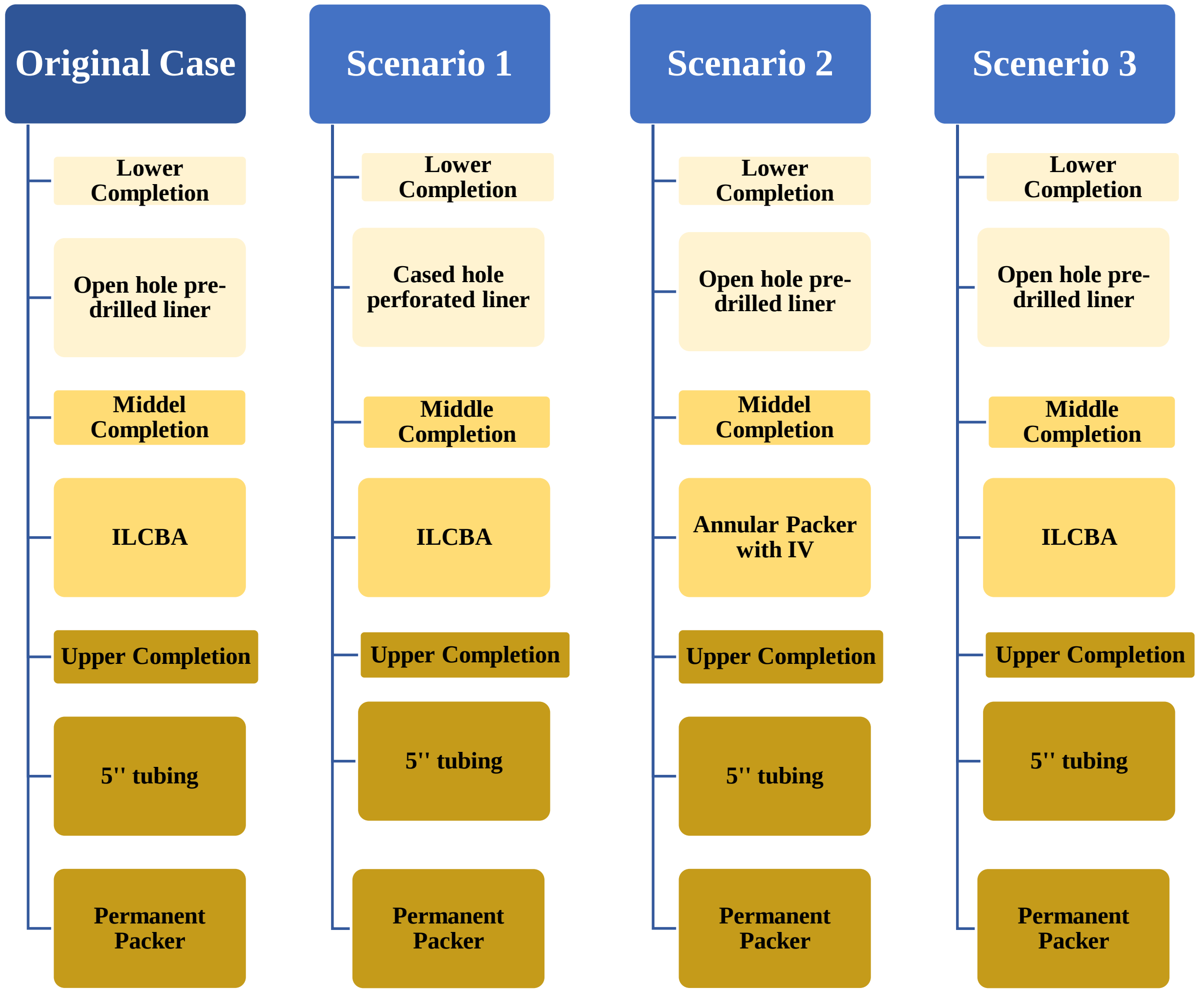

Figure 5.3 Sensitivity analysis of a case study

In Figure 5.3, the comparison of different scenario is shows as compared to the original case. In scenario 1 it is showing that the lower completion preference has been shifted to cased hole perforated liner while in original case it is open hole pre-drilled liner. In fuzzy TOPSIS software some of the inputs are changed to observe the change in final ranking of the alternatives. For scenario 1, the criteria weight has been altered and more decision makers are in favor of cased hole completion for well objective criteria. In the final ranking we get the 0.62 value for cased hole completion as compared to 0.57 value for open hole pre-drilled liner. In case of scenario 2, the middle completion has more ratings for annular packer with internal valve, 0.67 value, as compared to ILCBA, 0.65 value, and annular packer with downhole insulation valve, 0.61 value. The input parameters changed in scenario 2 are the number of decision makers for HS&E criteria for given alternatives. In scenario 3, it is observed that the ranking order for upper completion alternatives, permanent packer and retrievable, has not changed much though it suggests both options are reasonable to use as the difference in rating value is very small for both permanent and retrievable packer.

Sensitivity analysis necessitates that all variables, either dependent or independent, be evaluated in a definite way. It assists with deciding the relationship between the factors. Also, sensitivity analysis works with more precise determining.

5.3 Discussion and Summary

In this thesis a comprehensive model of fuzzy TOPSIS is developed including user friendly interface to select the optimum well completion model for reservoirs. The fuzzy TOPSIS model accuracy depends mainly on the expert knowledge and experience for their relevant fields. It then finally combines the experts input for the given criterions and alternatives to generate the optimum solution for well completion method. In numerical index methods for well completion selection there is a lack or no input from the experts for overall selection process, so fuzzy TOPSIS fills out this gap by providing the experts instruction during modelling the well completion models. In most of the previous applications of MCDM the weights were crisp deterministic numbers which can cause huge errors in decision making problems as it's challenging for humans to manually handle the large set of data. So, to overcome this problem, this thesis applies the fuzzy approach to deal with problems involving uncertain conditions. This fuzzy TOPSIS model can be modified and adjusted to select well completions for various reservoirs and company needs. The companies can adjust the weight of each criteria depending on their needs and goals. Moreover, this decision-making system is suitable for oil companies as it has a flexibility of any changes whether they are related to any experts' requirements or data sets. In fuzzy TOPSIS it is also possible to apply it for selecting equipment for well completion by setting the criteria and involving the alternatives (desired equipment) to obtain final ratings of the equipment. To get the better and accurate results for the decision-making problems it is recommended to integrate the various MCDM methods to observe the final results as every method comes with its own specialty.

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