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Petroleum and Gas Reserves Exploration by Real-Time Expert Seismology and Non-Linear Seismic Wave Motion

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Abstract

By using a non-linear 3-D elastic waves real-time expert system, the new theory of "*Non-linear Real-Time Expert Seismology*" is investigated, for the exploration of the on-shore and off-shore petroleum and gas reserves all over the world. Such a highly innovative and groundbreaking technology is working under Real Time Logic for searching the on-shore and off-shore hydrocarbon reserves developed on the continental crust and in deeper water ranging from 300 to 3000 m, or even deeper. Consequently, this real-time expert system, will be the best device for the exploration of the continental margin areas (shelf, slope and rise) and the very deep waters, as well. The proposed modern technology can be used at any depth of seas and oceans all over the world and for any depth in the subsurface of existing oil reserves.

Beyond the above, the various mechanical properties of rock regulating the wave propagation phenomenon appear as spatially varying coefficients in a system of time-dependent hyperbolic partial differential equations. The propagation of the seismic waves through the earth subsurface is described by the wave equation, which is then reduced to a Helmholz differential equation. Furthermore, the Helmholtz differential equation is numerically evaluated by using the Singular Integral Operators Method (S.I.O.M.). Several properties are further analyzed and investigated for the wave equation.

Finally, an application is proposed for the determination of the seismic field radiated from a pulsating sphere into an infinite homogeneous medium. Thus, by using the S.I.O.M., then the acoustic pressure radiated from the above pulsating sphere is determined.

Key words: Non-linear real-time expert seismology; Singular integral operators method (S.I.O.M.); Time-dependent hyperbolic partial differential equations; Oil and gas reserves; Petroleum reservoir engineering; Helmholtz differential equation; Real-time expert system; Wave equation

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INTRODUCTION

The new method "*Non-linear Real-Time Expert Seismology*" is the main and best tool which can be used by the petroleum and gas industry to map hydrocarbon deposits in the Earth's upper crust. Furthermore, environmental and civil engineers can use variants of the above very modern technique to locate bedrock, acquifers, and other near-surface features and academic geophysicists can extend it to a tool for imaging the lower crust and mantle. The new technology of "*Non-linear Real-Time Expert Seismology*" was proposed and investigated by Ladopoulos (2011b, 2011c, 2012a, 2012b, 2012c, 2012d), as an extension on his methods on non-linear singular integral equations in fluid mechanics, potential flows, hydraulics, aerodynamics, structural analysis and solid mechanics (Ladopoulos, 1991, 1994, 1995a, 1995b, 1997, 2000a, 2000b, 2003, 2005, 2011a).

In general, seismic wave propagation, the physical phenomenon underlying the "*Non-linear Real-Time Expert Seismology*" as well as other types of seismology, is modeled with reasonable accuracy as small-amplitude displacement of a continuum, using various specializations and generalizations of linear elastodynamics. In such models, the various mechanical properties of rock regulating the wave propagation phenomenon appear as spatially varying coefficients in a system of time-dependent hyperbolic partial differential equations.

The "*Non-linear Real-Time Expert Seismology*" is applied by extracting maps of the Earth's sedimentary crust from transient near-surface recording of echoes, stimulated by explosions or other controlled sound sources positioned near the surface. Reasonably accurate models of seismic energy propagation take the form of hyperbolic systems of partial differential equations, in which the coefficients represent the spatial distribution of various mechanical characteristics of rock, like density, stiffness, etc. The exploration geophysics community has developed various methods for estimating Earth structure from seismic data, however the very modern method "*Non-linear Real-Time Expert Seismology*" seems to be the best tool for on-shore and off-shore oil and gas reserves exploration for very deep drillings ranging up to 20,000 or 30,000 m.

During the past years several variants of integral equations methods were used for the solution of elastodynamic and acoustic problems. As a beginning approximately at the end of sixty's Shenk (1968) stated that the integral equation for potential mathematically failed to yield unique solutions to the exterior acoustic problem and proposed a method in which an over determined system of equations at some characteristic frequencies was formed by combining the surface Helmholtz equation with the corresponding interior Helmholtz equation. It was analytically proved, that the system of equations to provide a unique solution at the same characteristic frequencies, to some extent. However, the above method might fail to produce unique solutions, when the interior points used in the collocation of the Boundary Integral Equations were located on a nodal surface of an interior standing wave.

Beyond the above, at the beginning of seventy's Burton and Miller (1971) proposed a combination of the surface Helmholtz integral equation for potential and the integral equation for the normal derivative of potential at the surface, to circumvent the problem of nonuniqueness at characteristic frequencies. Their method was called Composite Helmholtz Integral Equation. Some time later, Meyer, Bell, Zinn and Stallybrass (1978) and Terai (1980), developed regularization techniques for planar elements for the calculation of sound fields around three dimensional objects by integral equation methods.

On the contrary, Reut (1985), investigated further the Composite Helmhholtz Integral Equation Method by introducing the hypersingular integrals. Also, in the above numerical method, the accuracy of the integrations affects the results and the conventional Gauss quadrature can not be used directly.

The basic idea by using the gradients of the fundamental solution to the Helmholtz differential equation for velocity potential, as vector test functions to write the weak form of the original Helmholtz differential equation for potential and so directly to derive a non hypersingular boundary integral equations for velocity potential gradients, was introduced by Okada, Rajiyah and Atluri (1989) and Okada and Atluri (1994). They used the displacement and velocity gradients to directly establish the numerically tractable displacement and displacement gradient boundary integral equations in elasto-plastic solid problems and traction boundary integral equations. Beyond the above, Chien, Rajiyah and Atluri (1990), employed some known identities of the fundamental solution from the associated interior Laplace problem, to regularize the hypersingular integrals.

Also, Wu, Seybert and Wan (1991), proposed the regularized normal derivative equation, to be converged in the Cauchy principal value sense. The computation of tangential derivatives was required everywhere on the boundary. Moreover, Hwang (1997), reduced the singularity of the Helmholtz integral equation by using some identities from the associated Laplace equation. On the other hand, the value of the equipotential inside the domain must be computed, because the source distribution for the equipotential surface from the potential theory was used to regularize the weak singularities.

The identities of the fundamental solution of the Laplace problem was also used by Yang (2000), to efficiently solve the problem of acoustic scattering from a rigid body. Furthermore, Yan, Hung and Zheng (2003), in order to solve the intensive computation of double surface integral, employed the concept of a discretized operator matrix to replace the evaluation of double surface integral with the evaluation of two discretized operator matrices.

On the contrary, Han and Atluri (2003) used further traction boundary integral equations for the solution of the Helmholtz equation. Also, recently was used by Atluri, Han and Shen (2003) the meshless method, as an alternative numerical method, to eliminate the drawbacks in the Finite Element Method and the Boundary Element Method.

In the present investigation, the Singular Integral Operators Method (S.I.O.M.) will be used for the solution of elastodynamic problems by using the Helmholtz differential equation. In this derivation the gradients of the fundamental solution to the Helmholtz differential equation for the velocity potential, will be applied. Furthermore, several basic identities governing the fundamental solution to the Helmholtz differential equation for the velocity potential are analyzed and investigated.

Consequently, by using the Singular Integral Operators Method (S.I.O.M.), then the acoustic velocity potential will be computed. Beyond the above, some properties of the wave equation, which is a Helmholtz differential equation, are proposed and investigated. Also, some basic properties of the fundamental solution will be derived.

Finally, an application is proposed for the determination of the seismic field radiated from a pulsating sphere into an infinite homogeneous medium. Thus, by using the Singular Integral Operators Method (SIOM), then the acoustic pressure radiated from the above pulsating sphere will be computed. This is very important in petroleum reservoir engineering in order the size of the reservoir to be evaluated.

Hence, the S.I.O.M. which was used with big success for the solution of several engineering problems of fluid mechanics, hydraulics, potential flows, aerodynamics, solid mechanics and structural analysis, are further extended in the present investigation for the solution of hydrocarbon reservoir engineering problems in elastodynamics.

1. NON-LINEAR REAL-TIME EXPERT SEISMOLOGY

As a general rule, off-shore operations consist of 90% of all data collected worldwide for petroleum and gas reserves exploration. Thus, the depth of the drillings are usually up to 6000 m, but sometimes in order to find big petroleum and gas reserves they may extend to 10,000 m or even to 15,000 m or 20,000 m. Furthermore, big oil companies and research organisations by studying geological surveys all over the world indicate that oil reserves do not necessarily end at the edge of the continental shelf. Consequently, there is serious expectation that main resources will be found in areas of thick sedimentary sequences developed on the continental crust. Hence, there are good possibilities for finding off-shore petroleum and gas reserves in deeper waters, too, ranging up to 2500 m to 3000 m, or even more.

Furthermore, the behavior of a reservoir and of the wells drilled to produce it, depends not only on the properties of the petroleum and gas, but also on a series of factors that may be termed as the "*properties of the environment*". Among these factors are such items as capillary-pressure effects, the reaction of rock when subjected to high stress, pressure and temperature gradients at the shallower levels in the Earth's crust and the influences of the compressibility as pressure are reduced by fluid withdrawals.

Setting the stage for all studies of reservoir performance is the physical nature of the reservoir itself, its location, structure, lithology, internal geometry and extent. There are four basic conditions that must be satisfied in order a geological formation, or a part thereof, should form a suitable reservoir, for example for the accumulation of hydrocarbons. These are porosity, permeability, seal and closure. The first defines the pore space in the rock-space in which the oil and gas may collect. Permeability is the attribute of the rock that permits the passage of fluid through it. Generally, it is a measure of the degree interconnectedness, of the pore space, but some reservoir (e.g. in the massive limestone deposits, or in igneous intrusions) depends for fluid flow on a network of fractures within the rock.

Moreover, the seal is the "cap" of the reservoir and prevents the oil and gas from leaking away. On the other hand, closure is a measure of the vertical extent of the sealed trap or, in the case of hydrocarbon accumulation bounded below by a moving body of water, of the "height" of the sealed trap where that height is measured along a line perpendicular to the oil-water contact.

Three general categories of resources can be mentioned for off-shore reserves: structural traps, stratigraphic traps and combination traps. Sometimes there was no trap along the path of the water/hydrocarbon mixture as it moved through the formation on its journey from the source beds. Sometimes those traps that were present were insufficient in volume to hold all of the hydrocarbons in the percolating stream and sometimes the seal of the trap was not perfect. In each of these circumstances, some of the hydrocarbons moved eventually into near-surface locations where most of the light ends evaporated over the years, leaving behind a heavy tarlike residue, so thick that it would no longer flow at ambient temperatures.

Elastic waves are sound waves, usually three-dimensional which may be transmitted through matter in any phase-solid, liquid, or gas. Generally, any body vibrating in air gives rise to such waves, as it alternately compresses and rarefies the air adjacent to its surfaces. Also, a body vibrating in a liquid, or in contact with a solid, likewise generates similar longitudinal waves. Of course the frequency of the waves is the same as the frequency of the vibrating body that produces them. So, there are two types of elastic waves produced: a) P-waves, which are primary or "compressional" waves, and b) S-waves, or shear waves.

Furthermore, wavelength of the wave is the distance between two successive maxima (or between any two successive points in the same phase) and is denoted by l. Since the waveform, travelling with constant velocity u, advances a distance of one wavelength in a time interval of one period, then it follows that the velocity of sound waves u is given by the following relation:

$$u = l\,v \tag{1}$$

in which v denotes the frequency.

As it is obvious, the velocity u differs when the sound waves are travelling through solid, liquid, or gas. In a solid the elastic waves are moving faster than in a liquid and the air, and in a liquid faster than in the air. Thus, if somebody is searching for example for off-shore oil resources over the sea, by transmitting sound waves, then there will be a difference in the velocity of the waves in the sea, the solid bottom and in a potential reservoir.

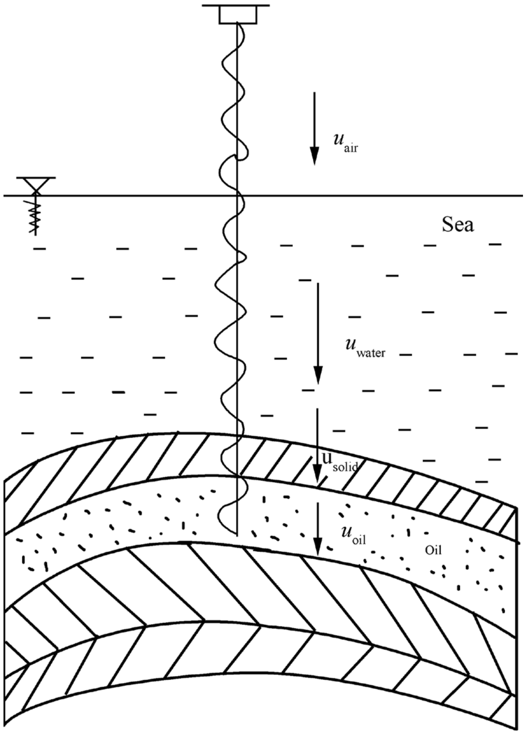

Figure 1
Elastic Waves Method for the Exploration of Oil Reserves

In order to better explain the new technology, consider the example of Figure 1. In this example consider that in the bottom of the sea there is a potential petroleum reservoir. In this case, the speed of the elastic waves in the air (u_{air}), will be different from the speed in the water (u_{water}), and different from the speed in the solid bottom (u_{solid}) and different from the speed in the potential reservoir (u_{oil}), while the frequency of the elastic waves remaining the same when transmitted through every different matter.

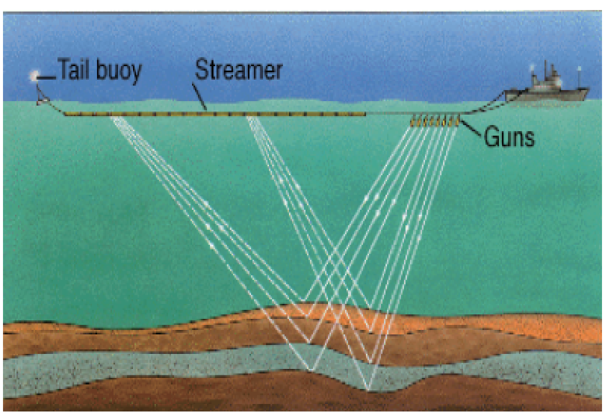

Figure 2
Real-Time Expert Seismology

Consequently, in the present research a real-time non-linear 3-D plane-polarized elastic waves expert system is proposed in order to explore the on-shore and off-shore petroleum and gas resources, according to the new theory of "*Real-Time Expert Seismology*", in contrast to the old theory of "*Reflection Seismology*" (Aki & Richards, 1980, Hale, 1984, Thomsen, 1988, 1999, Dellinger, 1993, Harrison & Stewart, 1993, Tsvankin & Thomsen, 1994, Alkhalifah & Tsvankin, 1995, Gaiser, 1997, Schmelzbach, Green & Horstmeyer, 2005, Schmelzbach, Horstmeyer & Juhlin, 2007). This new Sound Waves Technology will work under Real Time Logic for searching off-shore oil reserves developed on the continental crust and on deeper waters ranging from 300 m to 2500 m or 3000 m, or even much deeper (Figure 2). On the contrary, there are many deeper water prospects around the seas all over the world, but because of the paucity of the available information it is not possible at present to quantify the amounts that may be recoverable from them.

Thus, the proposed real-time elastic waves expert system will be the best device for the exploration of the continental margin areas (shelf, slope and rise) and the very deep waters ranging of more than 2500 ÷ 3000 m, too. Through the very modern technology of "*Non-linear Real-Time Expert Seismology*", will be effected the exploration of a significant part of on-shore and off-shore petroleum and gas reserves very fast and by a low cost.

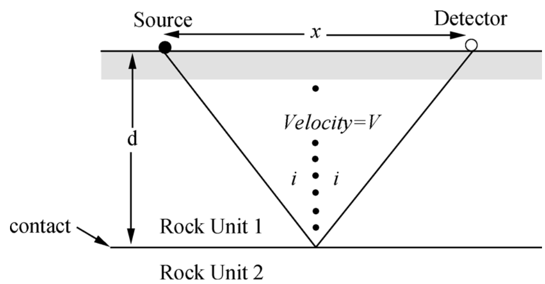

Figure 3
Law of Reflection

According to the proposed very modern technology of "*Non-linear Real-Time Expert Seismology*" the average velocity of the sound waves is calculated by providing important information about the composition of the solids through of which passed the sound waves. For example the velocity of the sound waves through the air is 331 m/sec, through liquid 1500 m/sec and through sedimentary rock 2000 to 5000 m/sec. Furthermore, according to the law of Reflection the angle of reflection equals the angle of incidence (Figure 3). Then according to the new method the arrival times of the seismic waves are analyzed. After the sensor measures the precise arrival time of the wave, then the velocity of the wave can be calculated by using the method as following.

The travel time T of the seismic waves is given by the relation:

$$T = \frac{2\left(d^2 + x^2/4\right)^{1/2}}{v} \tag{2}$$

Where d denotes the depth, x the distance between source of wave and the geophone or hydrophone detector and v is the average speed.

Beyond the above, from equation (2) follows equation (3):

$$T^2 = \frac{4d^2 + x^2}{v^2} \quad (3)$$

Also, the normal incident time T_o is given by the formula:

$$T_o = \frac{2d}{v} \quad (4)$$

From equations (3) and (4) follows:

$$T^2 - T_o^2 = \frac{x^2}{v^2} \quad (5)$$

Moreover, from equation (5) follows that the travel time curve for a constant velocity horizontal layer model is a hyperbola whose apex is at the zero-offset travel time T_o:

$$\frac{T^2}{T_o^2} - \frac{x^2}{(T_o v)^2} = 1 \quad (6)$$

Finally from equation (5) the mean velocity is equal to:

$$v = \frac{x}{\sqrt{T^2 - T_o^2}} \quad (7)$$

Hence, a real time expert system is proposed and the apparatus permitted excitation of any combination of elements and reception of any other, visual analysis of the responses, and transfer of the signals to the PC for post processing. The sequencing of transducer excitation, digitiser configuration and subsequent data analysis was performed by a rule based Real-Time Expert System. Then from the information gathered, the Expert System applies knowledge via a series of software coded rules and provides any one of the following conditions: speed in the water (u_{water}), speed in the solid bottom (u_{solid}) and speed in the potential reservoir (u_{oil}).

Real-time logic (RTL) is a reasoning system for real-time properties of computer based systems. RTL's computational model consists of events, actions, causality relations, and timing constraint (Jahanian & Mok, 1985, 1986; Emnis *et al*., 1986; Fritz, Haase, & Kalcher, 1988; Haase, 1990). This model is expressed in a first order logic describing the system properties as well as the systems dependency on external events. The Real-Time Logic system introduces time to the first logic formulas with an event occurrence function, which assign time values to event occurrences. Beyond the above, real-time computing in common practice is characterized by two major criteria: deterministic and fast response to external stimulation, and both human and sensor and actor based interaction with the external world. Real-time is an external requirement for a peace of software; it is not a programming technology.

In general, Real-Time Logic uses three types of constraints:

(1) Action constants may be primitive or composite. In a composite constant, precedence is imposed by the event-action model using sequential or parallel relations between actions.

(2) Event constants are divided into three cases. Start/stop events describe the initiation/termination of an action or subaction. Transition events are those which make a change in state attributes. This means, that a transition event changes an assertion about the state of the real-time system or its environment. The third class, which are the external events, includes those that can be impact the system behavior, but cannot be caused by the system.

(3) Integers assigned by the accurance function provide time values, and also denote the number of an event occurance in a sequence.

Furthermore, the Real-Time Logic System introduces time to the first order logic formulas with an event occurance function denoted by e. The mechanism to achieve a timing property of a system is the deduction resolution.

Consider further the following example: Upon pressing button ≠ 20, action TEST is extended within 300 time units. Dusting each execution of this action, the information is sampled and subsequently transmitted to the display panel. Also, the computation time of action TEST is 100 time units.

This example can be further translated into the following two formulas:

$$\forall\, x : e(\Omega \text{ button } 20, x) \le e(\uparrow \text{TEST}, x) \wedge$$
$$e(\downarrow \text{TEST}, x) \le e(\Omega \text{ button } 20, x) + 300$$
$$\forall\, y : e(\uparrow \text{TEST}, y) + 100 \le e(\downarrow \text{TEST}, y)$$

2. ELASTODYNAMICS BY NON-LINEAR SEISMIC WAVE MOTION

Generally, seismic wavelengths run in the tens of meters, so it is reasonable to presume that the mechanical properties of rocks responsible for seismic wave motion might be locally homogeneous on length scales of millimeters or less, which means that the Earth might be modeled as a mechanical continuum. Except possibly for a few meters around the source location, the wavefield produced in seismic reflection experiments does not appear to result in extended damage or deformation, so the waves are entirely transient. These considerations suggest a non-linear wave motion as a mechanical model in elastodynamics.

The equations of elastodynamics in homogeneous media are given as following:

$$\rho \frac{\partial v}{\partial t} = \nabla \bullet \sigma + b \tag{8}$$

$$\frac{\partial \sigma}{\partial t} = \frac{1}{2} C(\nabla v + \nabla v^T) + \gamma \tag{9}$$

In which v denotes the particle velocity field, σ the stress tensor, b a body force density, γ a defect in the elastic constitutive law, ρ the mass density, t the time and C the Hooke's tensor.

Moreover, the right hand sides b and γ provide a variety of representations for external energy input to the system.

The new technique for on-shore and off-shore oil and gas reserves exploration "*Non-linear Real-Time Expert Seismology*" uses transient energy sources and produce transient wave fields. Thus, the appropriate initial conditions for the system of equations (8) and (9) are:

$$v = 0, \quad \sigma = 0, \quad \text{for: } t << 0 \tag{10}$$

For isotropic elasticity, the Hooke's tensor has only two independent parameters, the compressional and shear wave speeds c_p and c_s. It is instructive to examine direct measurements of these quantities, made in a borehole. Thus, there are two types of elastic waves produced: a) P-waves, which are primary or "compressional" waves, and b) S-waves, or shear waves.

In the current investigation, the seismic problem will be not developed in the generalized context of the elastodynamic system equations (8) and (9). Instead, our research will be limited to a special case of seismology. Hence, in this present model, it is supposed that the material does not support shear stress. The stress tensor becomes scalar, $\sigma = -pI$, p being the pressure, and only one significant component, the bulk modulus κ, is left in the Hooke tensor.

Then, the system (8) and (9) reduces to:

$$\rho \frac{\partial v}{\partial t} = -\nabla p + b \tag{11}$$

$$\frac{1}{\kappa} \frac{\partial p}{\partial t} = -\nabla \bullet \mathbf{v} + h \tag{12}$$

Where the energy source is represented as a constitutive law defect h.

The proposed model predicts wave motion c with spatially varying wave speed:

$$c = \sqrt{\frac{\kappa}{\rho}} \tag{13}$$

With ρ the mass density and κ the bulk modulus.

Also, it is very convenient to represent the elastodynamics in terms of the acoustic velocity potential $u(x,t) = \int_{-\infty}^{t} p(x,s)ds$, which results to:

$$p = \frac{\partial u}{\partial t}$$

and:

$$\mathbf{v} = \frac{1}{\rho} \nabla u \tag{14}$$

By using equations (13) and (14), then the acoustic system equations (11) and (12) reduces to the wave equation, because of the propagation of seismic waves through an unbounded homogeneous solid:

$$\frac{1}{\rho c^2} \frac{\partial^2 u}{\partial t^2} - \nabla \bullet \frac{1}{\rho} \nabla u = h \tag{15}$$

Beyond the above, by assuming that density ρ is constant and that the source (transient constitutive law defect h) is an isotropic point radiator located at the source point, then the wave equation (15) reduces to the following Helmholtz differential equation:

$$\frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} - \nabla^2 u = 0 \tag{16}$$

For time harmonic waves with a time factor $e^{-i\omega t}$, then the wave equation (16) reduces to:

$$\nabla^2 u + k^2 u = 0 \tag{17}$$

Where the wave number k is equal to:

$$k = \frac{\omega}{c} \tag{18}$$

With ω the angular frequency and c the speed of sound in the medium at the equilibrium state.

The fundamental solution of the wave equation (8) at any field point **y** due to a point sound source **x**, for the two dimensions is given by the formula:

$$u^*(\mathbf{x},\mathbf{y}) = \frac{i}{4} H_0^{(1)}(kr) \tag{19}$$

$$\frac{\partial u^*}{\partial r}(\mathbf{x},\mathbf{y}) = -\frac{i}{4} k H_1^{(1)}(kr) \tag{20}$$

In which $i = \sqrt{-1}$, $H_0^{(1)}(kr)$ denotes the Hankel function of the first kind and r is the distance between the field point **y** and the source point **x** ($r = |\mathbf{x} - \mathbf{y}|$).

Furthermore, the fundamental solution of the wave equation (8) for the three dimensions is given as following:

$$u^*(\mathbf{x},\mathbf{y}) = \frac{1}{4\pi r}e^{-ikr} \tag{21}$$

$$\frac{\partial u^*}{\partial r}(\mathbf{x},\mathbf{y}) = \frac{e^{-ikr}}{4\pi r^2}(-ikr-1) \tag{22}$$

The fundamental solution $u^*(\mathbf{x},\mathbf{y})$ is further governed by the wave equation:

$$\nabla^2 u^*(\mathbf{x},\mathbf{y}) + k^2 u^*(\mathbf{x},\mathbf{y}) + \Delta(\mathbf{x},\mathbf{y}) = 0 \tag{23}$$

Consequently, equation (23) is referred as the Helmholtz potential equation governing the fundamental solution.

Beyond the above, consider the weak form of the Helmholtz equation to be given by the relation:

$$\int_{\Omega} (\nabla^2 u + k^2 u)u^* d\Omega = 0 \tag{24}$$

In the solution domain Ω.

By applying further the divergence theorem once in (24), we obtain a symmetric weak form:

$$\int_{\partial\Omega} n_i u_{,i} u^* dS - \int_{\Omega} u_{,i} u_{,i}^* d\Omega - \int_{\Omega} k^2 u u^* d\Omega = 0 \tag{25}$$

In which **n** denotes the outward normal vector of the surface *S*.

Thus, in the symmetric weak form the function u and the fundamental solution u^* are only required to be first-order differentiable. Furthermore, by applying the divergence theorem twice in equation (24) then one has:

$$\int_{\partial\Omega} n_i u_{,i} u^* dS - \int_{\partial\Omega} n_i u u_{,i}^* dS + \int_{\Omega} u(u_{,ii}^* + k^2 u^*) d\Omega = 0 \tag{26}$$

So, equation (26) is the asymmetric weak form and the fundamental solution u^* is required to be second - order differentiable. Moreover, u is not required to be differentiable in the domain Ω.

By combining further equations (23) and (26), then we obtain:

$$u(\mathbf{x}) = \int_{\partial\Omega} n_i(\mathbf{y}) u_{,i}(\mathbf{y}) u^*(\mathbf{x},\mathbf{y}) dS - \int_{\partial\Omega} n_i(\mathbf{y}) u(\mathbf{y}) u_{,i}^*(\mathbf{x}.,\mathbf{y}) dS \tag{27}$$

Which can be further written as:

$$u(\mathbf{x}) = \int_{\partial\Omega} q(\mathbf{y}) u^*(\mathbf{x},\mathbf{y}) dS - \int_{\partial\Omega} u(\mathbf{y}) R^*(\mathbf{x},\mathbf{y}) dS \tag{28}$$

Where $q(\mathbf{y})$ denotes the potential gradient along the outward normal direction of the boundary surface:

$$q(\mathbf{y}) = \frac{\partial u(\mathbf{y})}{\partial n_v} = n_k(\mathbf{y}) u_{,k}(\mathbf{y}), \quad \mathbf{y} \in \partial\Omega \tag{29}$$

and the kernel function:

$$R^*(\mathbf{x},\mathbf{y}) = \frac{\partial u^*(\mathbf{x},\mathbf{y})}{\partial n_y} = n_k(\mathbf{y}) u_{,k}^*(\mathbf{x},\mathbf{y}), \quad \mathbf{y} \in \partial\Omega \tag{30}$$

By differentiating equation (28) with respect to x_k, one obtains the integral equation for potential gradients $u_{,k}(\mathbf{x})$ by the following relation:

$$\frac{\partial u(\mathbf{x})}{\partial x_k} = \int_{\partial\Omega} q(\mathbf{y}) \frac{\partial u^*(\mathbf{x},\mathbf{y})}{\partial x_k} dS - \int_{\partial\Omega} u(\mathbf{y}) \frac{\partial R^*(\mathbf{x},\mathbf{y})}{\partial x_k} dS \tag{31}$$

3. FUNDAMENTAL SOLUTION'S MATHEMATICAL PROPERTIES

The weak form of equation (13) governing the fundamental solution, can be rewritten as following:

$$\int_{\Omega} \left[\nabla^2 u^*(\mathbf{x},\mathbf{y}) + k^2 u^*(\mathbf{x},\mathbf{y})\right] c d\Omega + c = 0, \quad \mathbf{x} \in \Omega \tag{32}$$

In which c denotes a constant, considering as the test function.

Equation (32) can be further written as:

$$\int_{\Omega} \left[u_{,ii}^*(\mathbf{x},\mathbf{y}) + k^2 u^*(\mathbf{x},\mathbf{y})\right] d\Omega + 1 = 0, \quad \mathbf{x} \in \Omega \tag{33}$$

Furthermore, equation (33) takes the following form:

$$\int_{\partial\Omega} n_i(\mathbf{y}) u_{,i}^*(\mathbf{x},\mathbf{y}) dS + \int_{\Omega} k^2 u^*(\mathbf{x},\mathbf{y}) d\Omega + 1 = 0, \quad \mathbf{x} \in \Omega \tag{34}$$

Also, by considering an arbitrary function $u(x)$ in Ω as the test function, then the weak form of equation (12) may be written as:

$$\int_{\Omega} \left[\nabla^2 u^*(\mathbf{x},\mathbf{y}) + k^2 u^*(\mathbf{x},\mathbf{y}) + \Delta(\mathbf{x},\mathbf{y})\right] u(\mathbf{x}) d\Omega = 0, \quad \mathbf{x} \in \Omega \tag{35}$$

And further as:

$$\int_{\Omega}\left[u^*_{,ii}(\mathbf{x},\mathbf{y})+k^2u^*(\mathbf{x},\mathbf{y})\right]u(\mathbf{x})d\Omega+u(\mathbf{x})=0,\quad \mathbf{x}\in\Omega \tag{36}$$

Finally, equation (36) will be written as:

$$\int_{\partial\Omega}\Phi^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS+\int_{\Omega}k^2u^*(\mathbf{x},\mathbf{y})u(\mathbf{x})d\Omega+u(\mathbf{x})=0,$$

$$\mathbf{x}\in\Omega \tag{37}$$

Moreover, if $\mathbf{x}$ approaches the smooth boundary $(\mathbf{x}\in\partial\Omega)$, then the first term in equation (37) can be written as:

$$\lim_{x\to\partial\Omega}\int_{\partial\Omega}\Phi^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS=\int_{\partial\Omega}^{CPV}\Phi^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS-\frac{1}{2}u(\mathbf{x}) \tag{38}$$

In the sense of a Cauchy Principal Value (CPV) integral.

For the understanding of the physical meaning of equations (38), (34) and (37) can be written as following:

$$\int_{\partial\Omega}^{CPV}\Phi^*(\mathbf{x},\mathbf{y})dS+\int_{\Omega}k^2u^*(\mathbf{x},\mathbf{y})d\Omega+1/2=0,\quad x\in\partial\Omega \tag{39}$$

and:

$$\int_{\partial\Omega}^{CPV}\Phi^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS+\int_{\Omega}k^2u^*(\mathbf{x},\mathbf{y})u(\mathbf{x})d\Omega+1/2\,u(\mathbf{x})=0,$$

$$x\in\partial\Omega \tag{40}$$

From equation (39) follows that only a half of the source function at point $\mathbf{x}$ is applied to the domain Ω, when the point $\mathbf{x}$ approaches a smooth boundary, $\mathbf{x}\in\partial\Omega$.

Beyond the above, consider another weak form of equation (37) by supposing the vector functions to be the gradients of an arbitrary function $u(\mathbf{y})$ in Ω, chosen in such a way that they have constant values:

$$u_{,k}(\mathbf{y})=u_{,k}(\mathbf{x})\ ,\quad \text{for } k=1,2,3 \tag{41}$$

Consequently, the weak form of equation (37) can be written as:

$$\int_{\Omega}\left[u^*_{,ii}(\mathbf{x},\mathbf{y})+k^2u^*(\mathbf{x},\mathbf{y})\right]u_{,k}(\mathbf{y})d\Omega+u_{,k}(\mathbf{x})=0 \tag{42}$$

By applying further the divergence theorem, then equation (42) takes the form:

$$\int_{\partial\Omega}\Phi^*(\mathbf{x},\mathbf{y})u_{,k}(\mathbf{x})dS+\int_{\Omega}k^2u^*(\mathbf{x},\mathbf{y})u_{,k}(\mathbf{x})d\Omega+u_{,k}(\mathbf{x})=0 \tag{43}$$

Also, the following property exists:

$$\begin{aligned}&\int_{\partial\Omega}n_i(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,k}(\mathbf{x},\mathbf{y})dS-\int_{\partial\Omega}n_k(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,i}(\mathbf{x},\mathbf{y})dS\\&=\int_{\Omega}u_i(\mathbf{x})u^*_{,ki}(\mathbf{x},\mathbf{y})dS-\int_{\partial\Omega}u_{,i}(\mathbf{x})u^*_{,ik}(\mathbf{x},\mathbf{y})dS=0\end{aligned} \tag{44}$$

By adding equations (43) and (44) then one obtains:

$$\begin{aligned}&\int_{\partial\Omega}n_i(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,k}(\mathbf{x},\mathbf{y})dS-\int_{\partial\Omega}n_k(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,i}(\mathbf{x},\mathbf{y})dS\\&+\int_{\partial\Omega}\Phi^*(\mathbf{x},\mathbf{y})u_{,k}(\mathbf{x})dS+\int_{\Omega}k^2u^*(\mathbf{x},\mathbf{y})u_{,k}(\mathbf{x})d\Omega+\\&u_{,k}(\mathbf{x})=0\end{aligned} \tag{45}$$

Which takes finally the form:

$$\begin{aligned}&\int_{\partial\Omega}n_i(\mathbf{y})u_{,i}(\mathbf{x})u^*_{,k}(\mathbf{x},\mathbf{y})dS+\int_{\partial\Omega}e_{ikt}R_tu(\mathbf{x})u^*_{,i}(\mathbf{x},\mathbf{y})dS+\\&\int_{\Omega}k^2u^*(\mathbf{x},\mathbf{y})u_{,k}(\mathbf{x})d\Omega+u_{,k}(\mathbf{x})=0\end{aligned} \tag{46}$$

4. REGULARIZATION OF THE SINGULAR INTEGRAL OPERATORS METHOD

In the current section the regularization of the Singular Integral Operators Method will be considered together with the possibility of satisfying the SIOM in a weak form at $\partial\Omega$, through a generalized Petrov - Galerkin formula.

By subtracting equation (37) from equation (28), then one has:

$$\begin{aligned}&\int_{\partial\Omega}q(\mathbf{y})u^*(\mathbf{x},\mathbf{y})dS-\int_{\partial\Omega}\left[u(\mathbf{y})-u(\mathbf{x})\right]R^*(\mathbf{x},\mathbf{y})dS+\\&\int_{\Omega}k^2u^*(\mathbf{x},\mathbf{y})u(\mathbf{x})d\Omega=0\end{aligned} \tag{47}$$

Thus, by using equation (40), then equation (47) can be applied at point $\mathbf{x}$ on the boundary $\mathbf{x}\in\partial\Omega$, as following:

$$\int_{\partial\Omega} q(\mathbf{y})u^*(\mathbf{x},\mathbf{y})dS - \int_{\partial\Omega}\left[u(\mathbf{y})-u(\mathbf{x})\right]R^*(\mathbf{x},\mathbf{y})dS =$$

$$\int_{\partial\Omega}^{CPV} R^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS + \frac{1}{2}u(\mathbf{x}), \quad \mathbf{x}\in\partial\Omega \tag{48}$$

Beyond the above, the Petrov-Galerkin scheme can be used in order the weak form of equation (48) to be written as:

$$\int_{\partial\Omega} f(\mathbf{x})dS_x \int_{\partial\Omega} q(\mathbf{y})u^*(\mathbf{x},\mathbf{y})dS_y - \int_{\partial\Omega} f(\mathbf{x})dS_x \int_{\partial\Omega}[u(\mathbf{y}) -$$

$$u(\mathbf{x})]R^*(\mathbf{x},\mathbf{y})dS_y = \int_{\partial\Omega} f(\mathbf{x})dS_x \int_{\partial\Omega}^{CPV} R^*(\mathbf{x},\mathbf{y})u(\mathbf{x})dS_y +$$

$$\frac{1}{2}\int_{\partial\Omega} f(\mathbf{x})u(\mathbf{x})dS_x \tag{49}$$

In which $u(\mathbf{x})$ denotes a test function on the boundary $\partial\Omega$.

Furthermore, by using equation (40), then from equation (49) follows:

$$\frac{1}{2}\int_{\partial\Omega} f(\mathbf{x})u(\mathbf{x})dS_x = \int_{\partial\Omega} f(\mathbf{x})dS_x \int_{\partial\Omega} q(\mathbf{y})u^*(\mathbf{x},\mathbf{y})dS_y -$$

$$\int_{\partial\Omega} f(\mathbf{x})dS_x \int_{\partial\Omega}^{CPV} R^*(\mathbf{x},\mathbf{y})u(\mathbf{y})dS_y \tag{50}$$

Finally, if one chooses the test function $f(\mathbf{x})$ in such way to be identical to a function which is energy-conjugate to $u(\mathbf{x})$, then the following Galerkin SIOM is obtained:

$$\frac{1}{2}\int_{\partial\Omega} \hat{q}(\mathbf{x})u(\mathbf{x})dS_x = \int_{\partial\Omega} \hat{q}(\mathbf{x})dS_x \int_{\partial\Omega} q(\mathbf{y})u^*(\mathbf{x},\mathbf{y})dS_y -$$

$$\int_{\partial\Omega} \hat{q}(\mathbf{x})dS_x \int_{\partial\Omega}^{CPV} R^*(\mathbf{x},\mathbf{y})u(\mathbf{y})dS_y \tag{51}$$

Consequently, equation (51) is referred to a symmetric Galerkin SIOM.

5. APPLICATION OF NON-LINEAR ELASTODYNAMICS BY A PULSATING SPHERE

The previous mentioned theory will be further applied to the determination of the seismic field radiated from a pulsating sphere into an infinite homogeneous medium (Figure 4).

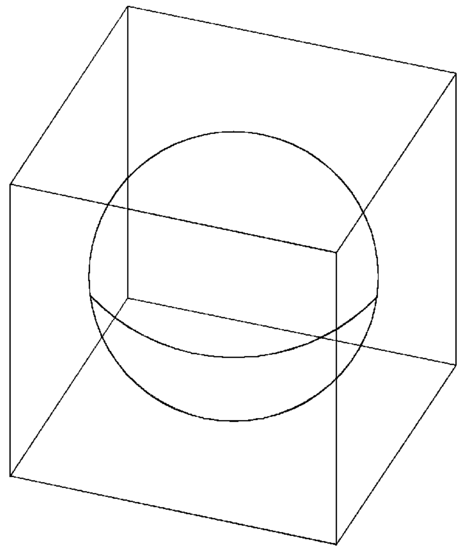

Figure 4
Field Radiated by a Pulsating Sphere into an Infinite Homogeneous Medium

Thus, by using the Singular Integral Operators Method (S.I.O.M.) as described in the previous paragraphs, then the computation of the acoustic pressure radiated from the above pulsating sphere is determined.

Beyond the above, the analytical solution of the acoustic pressure for a sphere of radius a, pulsating with uniform radial velocity v_a, is given by Chien (1990):

$$\frac{p(r)}{z_0 v_a} = \frac{a}{r}\frac{ika}{(1+ika)}e^{-ik(r-a)} \tag{52}$$

in which $p(r)$ denotes the acoustic pressure at distance r, z_0 is the characteristic impedance and k the wave number.

Thus, in Table 1 and Table 2, the real and imaginary parts of dimensionless surface acoustic pressures are shown with respect to the reduced frequency ka. So, the computational results by using the S.I.O.M. were compared to the analytical solutions of the same problem. From the above Tables it can be well seen that there is very small difference between the computational results and the analytical solutions. Finally same results are plotted, in Figures 5 and 6, and in three-dimensional form in Figures 5a and 6a.

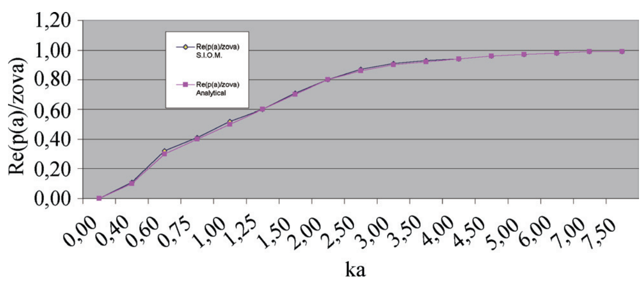

Figure 5
Real Part of Dimensionless Surface Acoustic Pressure of a Pulsating

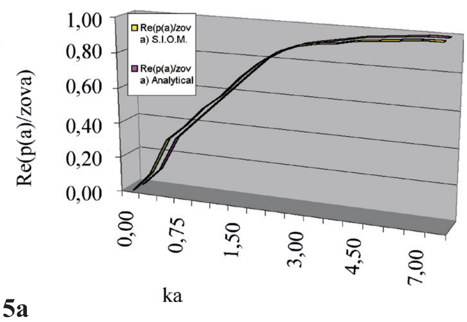

Figure 5a
3-D Distribution of Real Part of Dimensionless Surface Acoustic Pressure of a Pulsating

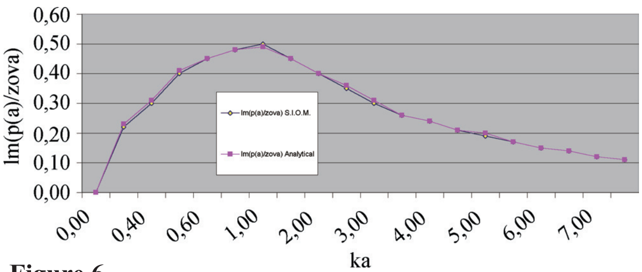

Figure 6
Imaginary Part of Dimensionless Surface Acoustic Pressure of a Pulsating

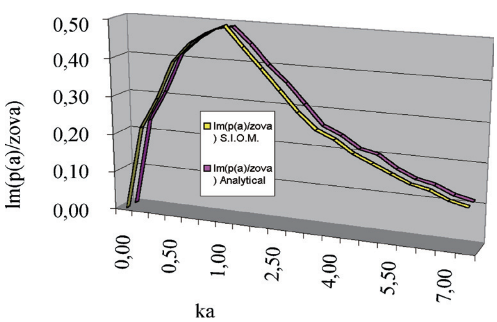

Figure 6a
3-D Distribution of Imaginary Part of Dimensionless Surface Acoustic Pressure of a Pulsating

Table 1
The Data of the Computational Results and Analytical Solutions

ka	$Re(p(a)/z_0v_a)$ Analytical	$Re(p(a)/z_0v_a)$ S.I.O.M.
0.00	0.00	0,00
0.40	0.10	0.11
0.60	0.30	0.32
0.75	0.40	0.41
1.00	0.50	0.52
1.25	0.60	0.60
1.50	0.70	0.71
2.00	0.80	0.80
2.50	0.86	0.87
3.00	0.90	0.91
3.50	0.92	0.93
4.00	0.94	0.94
4.50	0.96	0.96
5.00	0.97	0.97
6.00	0.98	0.98
7.00	0.99	0.99
7.50	0.99	0.99

Table 2
The Data of the Computational Results and Analytical Solutions

ka	$Im(p(a)/z_0v_a)$ Analytical	$Im(p(a)/z_0v_a)$ S.I.O.M.
0.00	0.00	0,00
0.20	0.22	0.23
0.40	0.30	0.31
0.50	0.40	0.41
0.60	0.45	0.45
0.80	0.48	0.48
1.00	0.50	0.49
1.50	0.45	0.45
2.00	0.40	0.40
2.50	0.35	0.36
3.00	0.30	0.31
3.50	0.26	0.26
4.00	0.24	0.24
4.50	0.21	0.21
5.00	0.19	0.20
5.50	0.17	0.17
6.00	0.15	0.15
6.50	0.14	0.14
7.00	0.12	0.12
7.50	0.11	0.11

CONCLUSIONS

The new technology of "*Non-linear Real-time Expert Seismology*" is used for the exploration of on-shore and off-shore petroleum and gas reserves. This very modern theory can be used at any depth of seas and oceans all over the world ranging from 300 to 3000 m, or even deeper and for any depth like 20,000 m or 30,000 m in the subsurface of existing oil and gas reserves.

The benefits of the new theory of "*Non-linear Real-time Expert Seismology*" in comparison to the old theory of "*Reflection Seismology*" are the following:

(1) The new theory uses the special form of the crests of the geological anticlines of the bottom of the sea, in order to decide which areas of the bottom have the most possibilities to include petroleum.

On the other hand, the existing theory is only based to the best chance and do not include any theoretical and sophisticated model.

(2) The new theory of elastic (sound) waves is based on the difference of the speed of the sound waves which are traveling through solid, liquid, or gas. In a solid the elastic waves are moving faster than in a liquid and the air, and in a liquid faster than in the air. Existing theory is based on the application of Snell's law and Zoeppritz equations, which are not giving good results, as these which we are expecting with the new method.

(3) The new theory is based on a Real-time Expert System working under Real Time Logic, that gives results in real time, which means every second.

Existing theory does not include real time logic.

From the above three points it can be well understood the evidence of the applicability of the new method of

"*Non-linear Real-time Expert Seismology*". Also its novelty, as it is based mostly on a theoretical and very sophisticated Real-time Expert model and not to practical tools like the existing method.

Furthermore, in the present research, the Singular Integral Operators Method (S.I.O.M.) has been used for the solution of the elastodynamic problems used in "*Non-linear Real-time Expert Seismology*" by applying the Helmholtz differential equation. In such a derivation the gradients of the fundamental solution to the Helmholtz differential equation for the velocity potential, has been used. Also, several basic identities governing the fundamental solution to the Helmholtz differential equation for the velocity potential were analyzed and investigated.

Thus, by using the S.I.O.M., then the acoustic velocity potential has be computed. Beyond the above, several properties of the wave equation, which is a Helmholtz differential equation, were proposed and investigated. Also, some basic properties of the fundamental solution have been derived.

Finally, an application was given for the determination of the seismic field radiated from a pulsating sphere into an infinite homogeneous medium. Consequently, by using the S.I.O.M., then the acoustic pressure radiated from the above pulsating sphere has be computed. This is very important in hydrocarbon reservoir engineering in order the size of the reservoir to be evaluated.

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Fuzzy Comprehensive Evaluation in Well Control Risk Assessment Based on AHP: A Case Study

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Abstract

To give a quantitative description of well control risk, a multi-layer fuzzy comprehensive evaluation based on AHP (analytic hierarchy process) is used. During the evaluation, risk factors and weight are given by Delphi method and AHP method. A multi-level and multi-factor evaluation system is built including four level-one factors of geologic uncertainty, well control equipments, techniques and crew quality, and fourteen level-two factors. Then a calculation is given with an oilfield in West China. The result shows geologic uncertainty is the primary factor leading to well control risks and the grade of well control risk is "higher risk". The application result indicates that well control risk assessment by fuzzy comprehensive evaluation is feasible.

Key words: Risk assessment; Fuzzy comprehensive evaluation; Analytic hierarchy process; Weight; Risk factor

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NOMENCLATURE

A = Target factor in Figure 2
$B_1, B_2, \ldots, B_4$ = First-level factors in Figure 2
$C_1, C_2, \ldots, C_{14}$ = Second-level factors in Figure 2
$\boldsymbol{A}$ = Judgment matrix of the four factors including $B_1, B_2, \ldots, B_4$
$\boldsymbol{W}$ = Weight of factors including $B_1, B_2, \ldots, B_4$
$\boldsymbol{W_1}$ = Weight of factors including C_1, C_2 and C_3
$\boldsymbol{W_2}$ = Weight of factors including $C_4, C_5, \ldots, C_7$
$\boldsymbol{W_3}$ = Weight of factors including $C_8, C_9, \ldots, C_{11}$
$\boldsymbol{W_4}$ = Weight of factors including C_{12}, C_{13} and C_{14}
$\boldsymbol{V}$ = Fuzzy evaluation set
$\boldsymbol{R}$ = Evaluation matrix of factors including $B_1, B_2, \ldots, B_4$
$\boldsymbol{R_1}$ = Evaluation matrix of factors including C_1, C_2 and C_3
$\boldsymbol{R_2}$ = Evaluation matrix of factors including $C_4, C_5, \ldots, C_7$
$\boldsymbol{R_3}$ = Evaluation matrix of factors including $C_8, C_9, \ldots, C_{11}$
$\boldsymbol{R_4}$ = Evaluation matrix of factors including C_{12}, C_{13} and C_{14}
$\boldsymbol{D}$ = Total evaluation matrix of the well control risk
$\boldsymbol{D_1}$ = Evaluation matrix of factor B_1
$\boldsymbol{D_2}$ = Evaluation matrix of factor B_2
$\boldsymbol{D_3}$ = Evaluation matrix of factor B_3
$\boldsymbol{D_4}$ = Evaluation matrix of factor B_4

INTRODUCTION

With the deep oil exploration and development, the engineering geologic conditions become more and more complex. Drilling equipments are increasingly large, and drilling technology becomes more complex[1,2]. This makes well control operations generate massive complex and uncertain factors, which results in great risk[3]. It plays an important guiding role in the wildcat well drilling to perform a careful risk identification and scientific risk evaluation of well control predrilling. In recent years, fuzzy comprehensive evaluation has been reported in risk assessment of drilling industry[4-7], which is visual with clear thinking and intuitive to understand. Besides, it is a quantitative analysis. At present, hazard operability study (HAZOP) and other qualitative methods are used to make a risk assessment in drilling[8-10]. But a quantitative risk assessment result cannot be obtained easily.

In this paper, we take the oilfield in western China as an example, establishing a multi-layer and multi-factor evaluation system including four level-one factors of geologic uncertainty, well control equipment, techniques and crew quality etc. and fourteen level-two factors through well control risk identification. A multi-layer fuzzy comprehensive evaluation is demonstrated step by step whose risk factor and weight is valued by Delphi method and AHP method. The evaluation result is analyzed and a prediction of well control risk is obtained. Results coincide with the actual drilling process through comparison, so it plays a guiding role to adopt fuzzy comprehensive evaluation to perform well control risk assessment for safe drilling before drilling.

1. MODEL OF WELL CONTROL RISK EVALUATION AND CALCULATIONS

An oilfield in west China is used to perform the well control risk assessment. This oilfield belongs to piedmont structure. Geologic structure is complicated and the foreseeability of geologic conditions is poor, which may cause serious discrepancy with the actual drilling. It is difficult to observe the sign at the preliminary stage of overflow in drilling. In this area, non-standard phenomenon in well control operation often occurs, which can cause potential well control risk. The overall situation of well control equipments is ordinary and the quality of staff in drilling crew is higher.

We invited twenty experts including five drilling engineers, five drilling safety engineers, five scholars in drilling engineering and five rig managers. They are all experienced drilling workers. Factors of the well control risk should be identified first by all the experts. Then a hierarchical framework of well control risk factors is established in terms of the subordinate relations. After the weight of each hierarchical factor is valued, we make fuzzy evaluation of the bottom level factors first. And its evaluation result is used as the matrix of membership degree for evaluation set as the single factor of the above layer which is gradually evaluated bottom up. As for the analysis of evaluation results, it is from the upper factors to the lower ones. The principle of simple two-level fuzzy comprehensive evaluation method is shown (Figure 1).

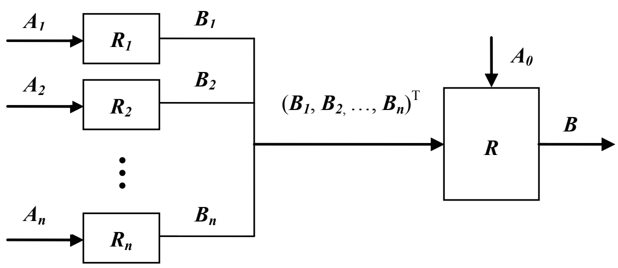

Figure 1
Diagram of Fuzzy Comprehensive Evaluation Method

1.1 Determination of Well Control Risk Factors

It's up to the twenty experts to discuss and decide the well control risk factors at the meeting. Each of them should submit as many factors as possible. According to the geologic characteristics of the oilfield above and the problems met in drilling, comprehensively considering the factors of operation and staff quality of the drilling crew[11], ignoring the secondary influencing factors in well drilling, a well control risk factor set is obtained. All risk factors are classified into two levels by affiliation. So a two-level skeleton of well control risk factor set is built (Figure 2).

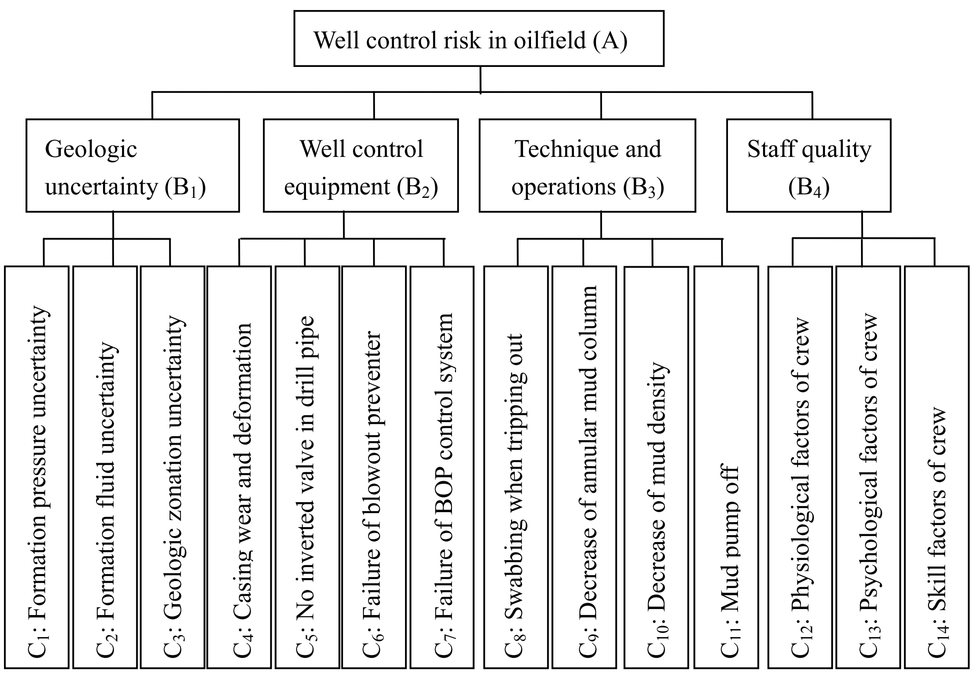

Figure 2
Skeleton of Well Control Risk Factor Set

Figure 2 is composed of four corresponding single well control risk factors in the first level as B_i (i = 1, 2, 3, 4) and fourteen more definite well control risk factors in the second level as C_i (i = 1, 2, …, 14).

1.2 Determining the Weight of Risk Factors in Each Level

The weight of each factor relative to the factor in upper level is calculated by AHP. AHP is an effective method for making decisions on complex problems. It adopts quantitative study for describing qualitative factors, which meets the need of weight distribution for factors of each level. First, a pairwise comparison of importance between every two risk factors such as X_1, X_2, …, X_n is necessary. Then natural number of 0 to 9 and its inverse is used to express the importance of every two factors by Table 1. This procedure is accomplished by the twenty experts. The experts judge the importance between factors collectively and reach an agreement on the result.

Table 1
Criterion of Factor's Important Intensity

Importance between X_i and X_j	X_{ij}	X_{ji}
X_i and X_j are the same important	1	1
X_i is a little more important than X_j	3	1/3
X_i is obviously more important than X_j	5	1/5
X_i is quite more important than X_j	7	1/7
X_i is absolutely more important than X_j	9	1/9
Importance between the above	one of 2, 4, 6, 8	one of 1/2, 1/4, 1/6, 1/8

After the comparison, a well control risk factor judgment matrix A_1 in this level is obtained:

$$A_1 = \begin{array}{c} \\ X_1 \\ X_2 \\ \vdots \\ X_n \end{array} \begin{array}{c} \begin{array}{cccc} X_1 & X_2 & \cdots & X_n \end{array} \\ \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \end{array}$$

If the matrix A_1 satisfies consistency check in mathematics, the eigenvalue of the matrix will be the weight of the factor including X_1, X_2, …, X_n. The calculation of the largest characteristic vector of well control risk judgment matrix and risk factor weight are as follows[5]:

Calculation of matrix A_1 is performed by each row: $w_i' = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$, i=1,2,…,n. So a new matrix $\boldsymbol{w}$ can be obtained as $\boldsymbol{w} = (w_1', w_2', \cdots, w_n')^T$. Normalize the matrix $\boldsymbol{w}$ according to the formula $w_i = w_i' / \sum_{j=1}^{n} w_j'$ (i=1,2,…,n). So the characteristic vector of the matrix A_1 can be obtained as the vector $\boldsymbol{W} = (w_1, w_2, \cdots, w_n)$. And the value of $w_1, w_2, \ldots w_n$ also means the weight of factors in matrix A_1. The largest eigenvalue of matrix A_1 can be calculated according to the formula $\lambda_{\max} = \sum_{i=1}^{n} (A_1 w)_i / n w_i$. During the calculation, $(A_1 w)_i$ is the i-th factor in vector $(A_1 w)$.

When the largest eigenvalue of matrix A_1 is determined, the judgment of consistency check in mathematics will be performed as the following two formulas[12]:

$$CI = (\lambda_{\max} - n)/(n-1), CR = CI/RI$$

In the formula mean random consistency index RI is valued in Table 2. If $CR \leq 0.1$, then the coincidence principle can be accepted. If the value of CR is not acceptable, the experts should discuss again. And a recalculation is made.

With regard to the four factors of B_1, B_2, B_3 and B_4 in the first level, the experts gives a judgment matrix collectively through discussion at the meeting and the weight of each factor can be obtained by the above calculation process (shown in Table 3).

Table 2
Mean Random Consistency Index RI

Order of matrix	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

Table 3
Fuzzy Comparison Matrix and Weight of Well Control Risk Factors

Evaluation matrix *A*	B_1	B_2	B_3	B_4	Weight of first level (*W*)	Check procedure
B_1	1	2	4	5	0.503	λ_{max}=4.17 *CI*=0.057 *CR*=0.063<0.1
B_2	1/2	1	4	2	0.283	
B_3	1/4	1/4	1	2	0.119	
B_4	1/5	1/2	1/2	1	0.095	

In Table 3, judgment matrix of the four factors is given by the experts as follow:

$$A = \begin{pmatrix} 1 & 2 & 4 & 5 \\ 1/2 & 1 & 4 & 2 \\ 1/4 & 1/4 & 1 & 2 \\ 1/5 & 1/2 & 1/2 & 1 \end{pmatrix}$$

The weight of the factors in first level is calculated by the procedure above. And the weight of the four factors is as follow:

$$W = (0.503, 0.283, 0.119, 0.095)$$

Similarly in the second level, factors of C_1, C_2, C_3; C_4, C_5, C_6, C_7; C_8, C_9, C_{10}, C_{11}; C_{12}, C_{13}, C_{14} are calculated respectively (Table 4). And the results are as follows:

W_1 = (0.539, 0.297, 0.164)

W_2 = (0.466, 0.095, 0.160, 0.278)

W_3 = (0.311, 0.465, 0.072, 0.152)

W_4 = (0.163, 0.297, 0.54)

2. WELL CONTROL RISK EVALUATION RESULTS AND ANALYSIS

2.1 Determining the Well Control Evaluation Set and Single Factor's Evaluation Matrix

Evaluation set is used to divide the single factors into grade. Well control risk fuzzy evaluation set is built as follows.

$\boldsymbol{V} = (v_1, v_2, v_3, v_4, v_5)$ = (higher risk, high risk, average risk, lower risk, low risk)

The risk degree of fourteen single factors in the second level is evaluated first. The grade of membership of the single factor C_j attached to the element v_m in evaluation set is calculated by the membership formula:

$r_{jm} = M_{jm}/N$

r_{jm} - membership to the element v_m in evaluation set;

M_{jm} - number of experts who think factor C_j is corresponding to element v_m in evaluation set;

N - total number of experts at the meeting.

So we can obtain the fuzzy evaluation matrix $\boldsymbol{R_i}$, which is composed of factors' membership magnitude included in factor B_i (i = 1,2,3,4). The evaluation matrix $\boldsymbol{R_i}$ is listed as the following form.

$$\boldsymbol{R_i} = \begin{matrix} \\ C_j \\ C_{j+1} \\ \vdots \\ C_{j+n} \end{matrix} \begin{matrix} v_1 & v_2 & \cdots & v_n \\ \left(\begin{matrix} r_{11} \\ r_{21} \\ \vdots \\ r_{n1} \end{matrix} \right. & \begin{matrix} r_{12} \\ r_{22} \\ \vdots \\ r_{n2} \end{matrix} & \begin{matrix} \cdots \\ \cdots \\ \ddots \\ \cdots \end{matrix} & \left. \begin{matrix} r_{1m} \\ r_{2m} \\ \vdots \\ r_{nm} \end{matrix} \right) \end{matrix}$$

In this process, the Delphi method is used to evaluate the grade of membership attached to the evaluation set. We send questionnaires to all the experts. Each of them evaluates every single factor (C_1, C_2, …, C_{14}) by choosing which element they belongs to in the evaluation set $\boldsymbol{V}$. Then we take back all the questionnaires and make a statistical analysis and calculate the membership with membership formula. The result of the single factor evaluation results are given by the drilling experts (Table 4). From Table 4 we can obtain the fuzzy evaluation matrix of the single factors included in the risk of geologic uncertainty, well control equipment, personal quality and technology and operations. The four evaluation matrixes are $\boldsymbol{R_1}$, $\boldsymbol{R_2}$, $\boldsymbol{R_3}$ and $\boldsymbol{R_4}$ as follows.

$$\boldsymbol{R_1} = \begin{matrix} C_1 \\ C_2 \\ C_3 \end{matrix} \begin{pmatrix} 0.500 & 0.250 & 0.125 & 0.125 & 0.000 \\ 0.250 & 0.500 & 0.125 & 0.125 & 0.000 \\ 0.125 & 0.250 & 0.500 & 0.125 & 0.000 \end{pmatrix} \quad (\text{higher, high, average, low, lower})$$

$$\boldsymbol{R_2} = \begin{matrix} C_4 \\ C_5 \\ C_6 \\ C_7 \end{matrix} \begin{pmatrix} 0.250 & 0.375 & 0.250 & 0.125 & 0.000 \\ 0.125 & 0.500 & 0.250 & 0.125 & 0.000 \\ 0.000 & 0.125 & 0.375 & 0.375 & 0.125 \\ 0.250 & 0.375 & 0.250 & 0.125 & 0.000 \end{pmatrix} \quad (\text{higher, high, average, low, lower})$$

$$\boldsymbol{R_3} = \begin{matrix} C_8 \\ C_9 \\ C_{10} \\ C_{11} \end{matrix} \begin{pmatrix} 0.250 & 0.375 & 0.250 & 0.125 & 0.000 \\ 0.375 & 0.250 & 0.125 & 0.125 & 0.125 \\ 0.000 & 0.375 & 0.375 & 0.125 & 0.125 \\ 0.125 & 0.250 & 0.375 & 0.125 & 0.125 \end{pmatrix} \quad (\text{higher, high, average, low, lower})$$

$$\boldsymbol{R_4} = \begin{matrix} C_{12} \\ C_{13} \\ C_{14} \end{matrix} \begin{pmatrix} 0.000 & 0.000 & 0.125 & 0.625 & 0.250 \\ 0.125 & 0.250 & 0.250 & 0.250 & 0.125 \\ 0.125 & 0.250 & 0.375 & 0.125 & 0.125 \end{pmatrix} \quad (\text{higher, high, average, low, lower})$$

Table 4
Weight of Each Level and Single-Factor Evaluation Matrix

First-level factors	Weight of first level factors (W)	Second level factors	Weight of second level factors		Grade of risk (evaluation sets)				
					Higher	High	Average	Low	Lower
Geologic uncertainty B_1	0.503	C_1	$\boldsymbol{W_1}$	0.539	0.500	0.250	0.125	0.125	0
		C_2		0.297	0.250	0.500	0.125	0.125	0
		C_3		0.164	0.125	0.250	0.500	0.125	0
Well control equipment B_2	0.283	C_4	$\boldsymbol{W_2}$	0.466	0.250	0. 375	0.250	0.125	0
		C_5		0.095	0.125	0.500	0.250	0.125	0
		C_6		0.160	0	0.125	0.375	0.375	0.125
		C_7		0.278	0.250	0.375	0.250	0.125	0
Techniques & operations B_3	0.119	C_8	$\boldsymbol{W_3}$	0.311	0.250	0.375	0.250	0.125	0
		C_9		0.465	0.375	0.250	0.125	0.125	0.125
		C_{10}		0.072	0	0.375	0.375	0.125	0.125
		C_{11}		0.152	0.125	0.250	0.375	0.125	0.125
Staff quality B_4	0.095	C_{12}	$\boldsymbol{W_4}$	0.163	0	0	0.125	0.625	0.250
		C_{13}		0.297	0.125	0.250	0.250	0.250	0.125
		C_{14}		0.54	0.125	0.250	0.375	0.125	0.125

2.2 Multilevel Fuzzy Comprehensive Evaluation of Well Control Risk

The fuzzy comprehensive evaluation adopts fuzzy mathematics algorithm. During the calculation, the multiplication addition and multiplying operation in the ordinary matrix are replaced by taking the bigger and taking the smaller operations respectively[13-15]. After the calculation the second level results are normalized and the evaluation matrix $\boldsymbol{D_1}$, $\boldsymbol{D_2}$, $\boldsymbol{D_3}$ and $\boldsymbol{D_4}$ are obtained.

$\boldsymbol{D_1} = \boldsymbol{W_1}\boldsymbol{R_1}$ = (0.460, 0.273, 0.152, 0.115, 0.000)

$\boldsymbol{D_2} = \boldsymbol{W_2 R_2} = (0.216, 0.323, 0.216, 0.138, 0.107)$

$\boldsymbol{D_3} = \boldsymbol{W_3 R_3} = (0.316, 0.262, 0.212, 0.105, 0.105)$

$\boldsymbol{D_4} = \boldsymbol{W_4 R_4} = (0.116, 0.233, 0.349, 0.151, 0.151)$

According to the results of matrix $\boldsymbol{D_1}$, $\boldsymbol{D_2}$, $\boldsymbol{D_3}$ and $\boldsymbol{D_4}$, the first level factors' fuzzy evaluation set $\boldsymbol{R}$ can be gained.

$$\boldsymbol{R} = (\boldsymbol{D_1}, \boldsymbol{D_2}, \boldsymbol{D_3}, \boldsymbol{D_4})^T$$

Similarly the first level result of evaluation can be calculated as the following process.

$$\boldsymbol{D} = \boldsymbol{WR} = (0.460, 0.283, 0.216, 0.138, 0.107)$$

After normalization, vector $\boldsymbol{D}$ can be noted as the following form.

$$\boldsymbol{D} = (0.382, 0.235, 0.179, 0.115, 0.089)$$

2.3 Calculation Result Analysis

The frequently-used HAZOP method of well control risk assessment is to put the idea of risk analysis into each step of operations during well control. Through the deviation analysis of the technology or the variation of status parameter in well control process, we can identify these changes and deviation's influences on system and the consequences. Then we can make an analysis of the causes and put forward the effective measures. It can only make a qualitative analysis for a certain well rather than some wells in one block zone. Also it cannot provide quantitative risk value. However, fuzzy comprehensive evaluation method can perform a risk assessment of well control not only for a certain well but also for a block of oilfield wells and can provide a quantitative risk value. We can get the following results from the front fuzzy comprehensive evaluation process of well control risk in western oilfield:

(1) According to the principle of maximum membership degree, from the first-level evaluation result $\boldsymbol{D}$, we can conclude the overall well control risk of the oilfield is "higher risk" level. The possibility of "higher risk" and "high risk" level accounts for 61.7%. In the initial drilling of several wildcat in this oilfield, such complicated situations as well kick, overflow and leakage often appears, which is consistent with the evaluation.

(2) From Table 3, in the first level of risk factors, geologic uncertainty risk and risk of well control equipment account for 50.3% and 28.3% respectively. From further risk identification of both, we can see the biggest risk points of the second level are respectively the uncertainty of formation pressure and casing deformation. The membership degree of both risk points are respectively "higher risk" and "high risk".

(3) From the analysis process, it is concluded that geologic predicted risk is the most important factor of causing high risk. Therefore, we ought to increase the exploration of this block and enhance the precision of prediction of geologic prospecting. In addition, we still need to improve the reliability of well control equipment and well control process operation in order to reduce well control risk of the block.

CONCLUSIONS AND SUGGESTIONS

(1) Fuzzy comprehensive evaluation method of well control risk, which integrated multilevel well control risks, avoids the limitations of using single index evaluation. This method has combined qualitative study with quantitative study to make the evaluation results more reasonable and accurate.

(2) Though there are subjective influence in experts' Delphi method and importance judgment of risk factors, experts' Delphi method is finished collectively, which makes the error reduce. And analytic hierarchy process weakens the subjectivity importance judgment of risk factors.

(3) The following actual drilling process of western oilfield in China shows that using fuzzy comprehensive evaluation method for well control risk assessment based on AHP before drilling is feasible.

(4) According to different situations of each oilfield, it can better instruct on-site construction and enhance drilling safety to establish risk system to do fuzzy comprehensive evaluation. This requires a further identification of well control risk factors, which makes risk system structure more reasonable.

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The Way Forward for Deepwater and Ultra Deepwater Drilling in Trinidad and Tobago

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Abstract

Future deepwater drilling in Trinidad and Tobago will definitely present enormous challenges. During the period 1999 to 2003, eight deepwater wells were drilled in deepwater acreage. None of these wells found hydrocarbon in economic quantities although abundant reserves have been found in the shelf area (<1000 meters water depth).

The data from these wells would be useful for further deepwater and ultra deepwater drilling in Trinidad. To date, no wells have been drilled in our ultra deepwater acreage but seismic acquisition and processing has been undertaken. Thus lessons learned from the first deepwater campaign will definitely propel the way forward for further exploration works in deeper waters. We have to adapt our operations to accommodate the problems associated with our first phase of deepwater drilling in our area.This paper will look at the approaches we should adapt in the next phase of deepwater drilling. Some of these issues include rig selection, well location, well design and planning, environmental studies (wind, wave, climate etc.) and shallow hazard assessment. The key learnings from previous deepwater drilling events are useful in future operation in Trinidad and Tobago.

Key words: Deepwater drilling; Trinidad and Tobago

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Nomenclature

ADCP	=	Acoustic Doppler Current Profiler
BOP	=	Blow Out Preventer
BSR	=	Bottom Stimulating Reflector
DP	=	Dynamic Positioning
DPPS	=	Dynamic Positioning Safety Program
MEEA	=	Ministry of Energy and Energy Affairs
MWD	=	Measurement while Drilling
NBC	=	North Brazil Current
NE	=	North East
NECC	=	North Equatorial Counter Current
OSRO	=	Oil Spill Response Organization
Ppg	=	Pounds per gallon
PSC	=	Production Sharing Contract
PWD	=	Pressure While Drilling
ROV	=	Remote Operated Vehicle
SSE	=	South South East
SWF	=	Shallow Water Flows
TTDAA	=	Trinidad and Tobago Deepwater Area Acreage
VIV	=	Vortex Induced Vibrations

INTRODUCTION

Over the last decade exploring the deep waters beyond the shelf (>1000 meters) has been looked at with much anticipation. Figure 1 below shows the deepwater and ultra deepwater acreage offshore Trinidad. A water depth greater than 1000 m is considered deepwater while greater than 1500m is ultra deepwater drilling. The concession map shows the blocks in the deepwater and ultra deepwater acreage (TTDAA regions). Also shown in the map in the shaded region is the current block and licenses operating by oil and gas companies. Our first deepwater drilling ended in 2003 and since then no further drilling was done. Deepwater blocks were recently awarded (2011) and a new deepwater bid round has started. It is hoped that the next deepwater drilling campaign would commenced in the near future.

1. A LOOK BACK AT OUR FIRST DEEPWATER DRILLING CAMPAIGN

The government of Trinidad and Tobago uses Production Sharing Contracts (PSCs) as vehicles to achieve a comprehensive exploration program. The PSCs were awarded in 1998 for the deepwater blocks 25a, 25b, 26 and 27 (Rajnauth & Boodoo, 2004).

These contracts involved:

(1) Five year exploration phase work program.
(2) Exploration wells to minimum commitment depths.
(3) Acquisition and processing of seismic data.
(4) Signature bonuses.

The drilling phase of the exploration activities in the deepwater blocks produced many challenges. The eight (8) wells drilled in these blocks have not found hydrocarbons in commercial quantities. Results showed that some of the wells were unable to reach their technical objectives. As a result, the actual number of days and cost for some wells were less than originally planned. There were numerous drilling events that significantly impacted the operation and contributed to downtime. These include impacts from currents, shallow hazards, abnormal pressures, rig equipment failures and hole problems. The average non productive time (NPT) was between 18-20% of total well days for some wells. The total cost of the drilling campaign was estimated at $223 MMUSD and then NPT would be estimated at $40 MMUSD.

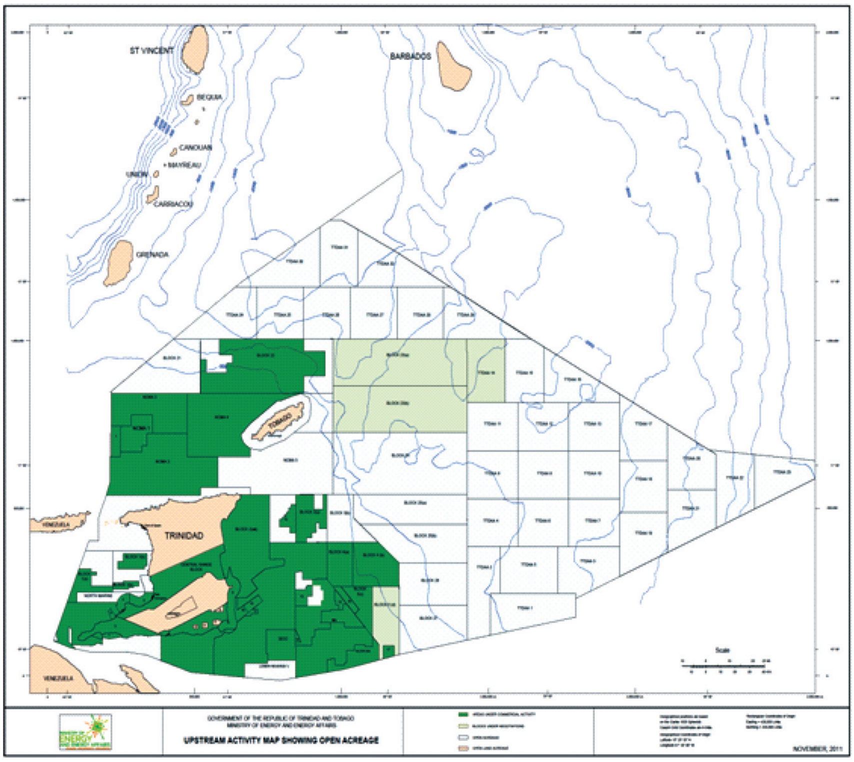

Figure 1
Concession Map of Trinidad and Tobago (MEEA, 2011)

2. IMPACTS ON DEEPWATER WATER DRILLING

Some of the issues that impacted our first deepwater drilling program are discussed below.

2.1 Meteorological and Oceanographic Impact

2.1.1 Weather and Met Ocean Conditions

The marine environment is characterized by wind driven waves predominately from easterly trade winds. Water swells are normally in the order of 2 m, increasing during periods of tropical storms. Wave regimes generally approach from the east, showing an annual shift towards the northeast during the period of January to February. The period between November to March coincides with winter storm activity in the North Atlantic Ocean, resulting in higher waves and rougher seas during this period and has impacted drilling operations.

2.1.2 Hurricanes

Trinidad and Tobago are generally considered to be slightly to the south of the hurricane belt. In the tropical region, the hurricane season normally extends from June to November. There have been over 25 hurricanes or storms affecting Trinidad and Tobago over the last century. One of the deepwater wells drilled in 1999 was suspended for an approaching hurricane; however, the storm deviated before crossing the location. While hurricanes have not severely impacted deepwater drilling operations in Trinidad, it is expected that tropical storms can have an impact on drilling operations in the future.

2.1.3 Currents

The drilling operations of several operators in deepwater blocks offshore Trinidad have been subjected to delays caused by high currents with current speeds in excess of 3 knots recorded. Currents had significant impact on several wells; on one well there were four (4) attempts at running riser with resulting downtime of 15.2 days (Table 1). It took about one week to run the Blow Out Preventer (BOP) and riser on another well. The drill ship actually went south in order to avoid strong currents. The highest recorded current during operations on another well was 3.3 knots, which occurred while running wireline logs. Additional casing running time was required due to severe problems experienced, stabbing and making up casing. There were major deflections of the casing joint in the slips caused by surface current deflecting the casing in the moon pool, however, conditions improved with depth/string weight. There was no evidence of vortex shedding, but the rig was able to maintainits position on location. Downtime from strong currents was estimated at about 23 days at a cost of $8 MMUSD for the eight deepwater wells drilled in Trinidad.

These currents are derived from North Brazil Current (NBC) that flows northwest along the coast of South America and turns north offshore Trinidad (Figure 3). Strong currents can have various effects on deepwater drilling operations, such as drilling downtime, riser installation delay and fatigue damage. Strong currents in deep water can produce vortex induced vibrations in moorings and risers. These vibrations can quickly cause fatigue damage and even loss of riser and well head. Delays to operations involving Remote Operated Vehicles (ROVs) because of currents throughout the water column are a common problem.

Table 1
Current Readings During Riser Running Problems

Depth (ft)	Current reading (knots)
Surface	2.8
289	2.5
663	2.3
1686	1.3

2.2 Shallow Hazards

Shallow hazards have impacted drilling operations on several deepwater wells drilled in Trinidad. One well had a shallow gas flow issue which was regarded as minor, slightly overpressure, with just a stream of bubbles observed at the wellhead. The flow was observed while drilling the pilot hole. The well was controlled with eleven pounds per gallon (11ppg) mud and flow checked before continuing operations. While running the BOP on riser during operations on another well, a flow was observed at the sea floor. This gradually increased and plumed up to forty-eight feet (48ft) in height (Figure 2). A pilot hole was then drilled to five thousand two hundred feet (5200 ft) and traces of bubbles were seen.

Figure 2
Shallow Water Flow Deepwater Trinidad

During the drilling operations of another well, the cameras on the ROV underwater showed a plume of gases around the BOP stack caused by a buildup of hydrates.

2.3 Well Design and Planning

The design and planning of the drilling programs for deepwater wells did not consider the planning of relief wells in case of an environmental issue. In the past the oil and gas operators would normally possess equipment to handle their own spills at a Tier 1 level. They would not normally stockpile equipment to manage a Tier 2 or Tier 3 incident within Trinidad and Tobago but the government of Trinidad and Tobago under the National Oil Spill Contingency plan will soon require operators to stock Tier 2 equipment or have access to it.

3. THE WAY FORWARD

3.1 Currents

Offshore operations are affected by all types and scales of current, from short-lived high-frequency variations that last just minutes to longer time-scale and more predictable features, such as tidal currents. NORSOK, a Norwegian initiative to reduce development and operation cost for the offshore oil and gas industry, recommends evaluating the following current components for structural design (Baynes, 2002): wind induced current, tidal current, coast and ocean current, local eddy current, currents over steep slopes, currents caused by storm surge and internal waves.

This list provides an overview of the current regimes that affect both the design and operation of offshore structures and vessels. It is not only surface currents that are important. Currents throughout the water column are important and especially the profile and vertical shear. It is not necessarily the intensity of the current that is most important. Current features that cause abrupt changes in the current at a specific location tend to have a greater effect on marine operations. For example, variability of the current profile over a timescale of minutes can cause problems in structures due to Vortex Induced Vibrations (VIVs).

The impact of currents on deepwater drilling operations could be reduced if there was access to reliable current measurements and/or forecasts. Information on currents is obtained from the following sources, either in near real-time or from archives: specific in situ measurements (e.g. drifting buoys, ADCPs, Radar), numerical models and remote sensing. Also of value is the local knowledge accumulated by seafarers and mariners, and this is often the only source of current information available.

The likely benefits to the offshore industry from improved current information are: reduced drilling downtime, reduced downtime in installations, improved safety, reduced costs of current impacts due to improved modeling capability and verification of models, reduced damage and losses from improved design, reduced costs associated with over-design or specification due to lack of current information, and more effective deployment of resources for in situ current measurements.

A combination of data sources and numerical modeling should be used by deepwater operators in Trinidad to provide effective current advisory information for their deepwater campaign. The regulatory body in Trinidad and Tobago should require operators to have a current monitor on the rig and the results from monitoring can be compiled in a Meteorological and Oceanographic data set for the country.

3.1.1 Formation and Migration Pattern of NBC Rings

Data from other studies are also useful in obtaining relevant data on currents that impact deepwater drilling operations offshore Trinidad. A study was done by Horizontal Marine Inc. on operational analysis of the NBC for 8 years from 2001 to 2009, using drifting buoys, satellite imagery, and Acoustic Doppler Currents (ADC). In this study, 44 NBC rings were researched to determine seasonal trends and find interannual variations (if any) in the formation and migration patterns of these rings. Figure 3 shows the Equatorial Atlantic circulation system showing the NBC movement to the Caribbean region.

The results showed that the maximum transport of water mass across the Atlantic Ocean occurs during the period June to August and minimum transport occurs during the period December to February. Thus, the NBC is only beginning to exhibit an increase in transport and intensity during spring and early summer (Sharma *et al.*). Due to its reduced intensity (during April-June), the NBC becomes coastally trapped and flows continuously along the northern coast of the South American continent. The North Equatorial Counter Current (NECC) ceases its eastward flow during the late spring and early summer and is replaced by a weak westward flow that does not influence the formation or migration of NBC rings. Thus, a lack of kinetic energy either prevents the NBC retroflection from forming altogether or allows for only a weak retroflection. Previous studies indicate that no NBC rings typically form during this time of the year and a relatively moderate flow is observed all along the northern coast of the South American continent and into the Caribbean Sea. Only one of our deepwater wells was drilled between April and June and this well did not encounter any problems due to high currents. All of the other wells were drilled between October to December and January to March when the NBC averaged higher ring size.

This is a basin scale current system that is driven primarily by the trade winds. Typical surface currents within the NBC range from 1 to 3 knots. The NBC currents decrease with depth and extend down to 1000m. NBC rings propagate at speeds averaging between 8 and 20 km/day, remain intact for up to 150 days, and have diameters ranging from 100 to 500 km. Surface currents within these rings circulate anti-cyclonically (clockwise) and may at times exceed 3.0 knots. Significant subsurface ring currents can extend as deep as 400m.

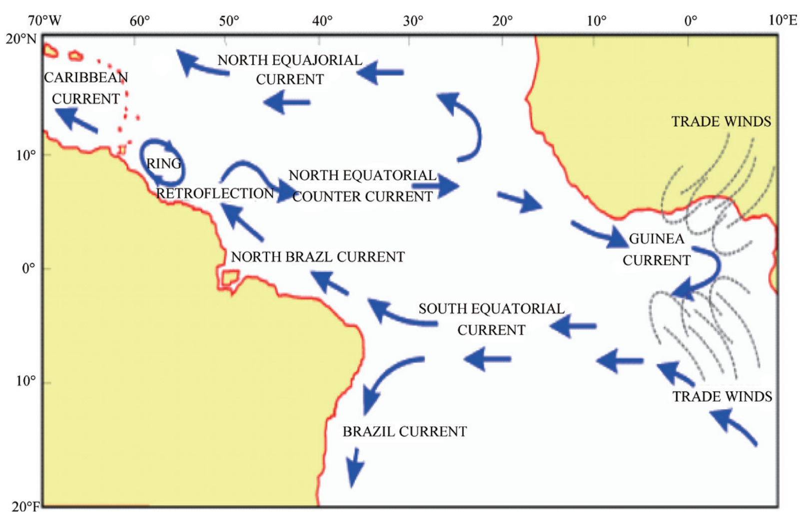

Figure 3
Equatorial Atlantic Circulation System (Sharma, *et al.*)

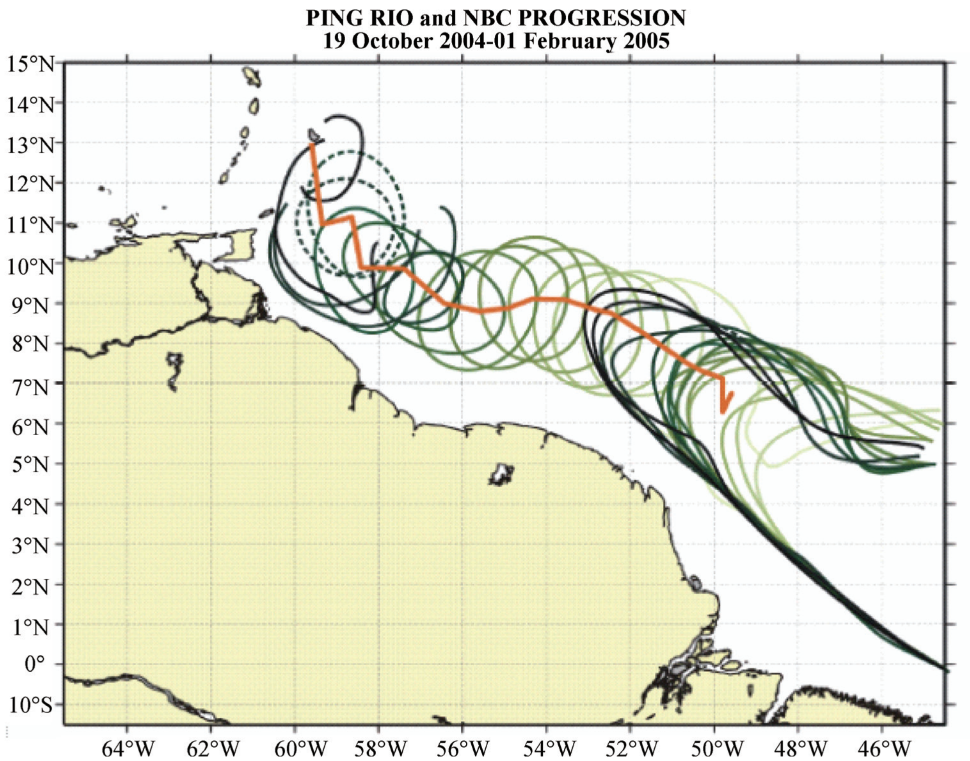

Figure 4
NBC Ring Progression over 3 Months (Sharma, *et al.*)

Figure 4 shows the weekly progression of a typical ring over a 3-month period during the NBC seasonal peak export in boreal fall and winter. Upon encountering the islands of Trinidad and Tobago, the ring changes its course of migration to move northward. From the concession map (Figure 1) it can be seen that most of the deepwater and ultra-deepwater blocks are in the region of 10 N to 12 N latitudes and 58 W to 60 W longitudes. Therefore the NBC can have tremendous impact on operations in deep acreages. The study also showed the general decrease in ring activity during late spring and early summer and increased activity in the second half of the year. The rings that do form in this season tend to have shorter life spans. Deepwater Operators may want to consider drilling wells during the April to June period to minimize impact on drilling operations from high currents.

Some of the possible mitigations include:

Monitoring of the weather and currents at and around the deepwater drilling location should commence as early as possible in the well planning phase. Historical met-ocean data and daily updates with weekly (and longer) forecasts are available from numerous commercial sources including ocean routes and storm data. Using the latest generation current meters would be extremely useful.

Historical and actual eddy current data are available from Eddy Watch groups. This data can provide the basis for contingency planning, as well as a guide to the likely occurrence of a high current event at a particular deepwater drilling location. Caribbean Met Ocean Statistics (CARIMOS) consists of a set of wind and wave hind cast data and extra-tropical storm data, with a description of regional climatology. It is one of the most comprehensive meteorological and oceanographic set of data for the Caribbean that meets offshore engineering requirements. This was developed by both Fugro GEOS and OceanweatherInc, who has drawn on 20 years' experience in pioneering state-of-the-art, met ocean studies to produce engineering descriptions of the environment (GEOS, 2012).

A detailed riser analysis is recommended prior to commencing any deepwater operations. An important objective of the analysis should be to identify what approaching current conditions would require the well to be secured and the riser pulled.

A disconnect criteria should be established such that the operations personnel clearly understand under what conditions the riser should, and should not, be disconnected. A disconnect decision matrix would be one approach to assist operations personnel in their understanding of the numerous and varied issues surrounding the disconnect decision and the establishment of the disconnect criteria (IADC, 2002).

The best period to drill deepwater wells in Trinidad is April to June from Horizontal Marine Inc. study. However, it is recommended that any operator planning to drill offshore Trinidad through the loop current season should have an alternative work location ready for the rig prior to the startup of a deepwater campaign. Eddy and loop current events generally tend to be of longer duration than hurricanes, affecting drilling locations for up to several weeks. For these reasons the risk mitigation of having an alternative location available during the loop current season can pay significant dividends.

The key is to select a vessel capable of handling currents up to and above 4 knots. The wells drilled in Trinidad experienced currents as high as 3.7 knots. Evaluating available technology such as non rotating drill pipe protectors; flex joint wear bushing, and fairings is important. Installing fairings on the riser help reduce VIV and are very useful in the high current portion of the water current.

3.2 Shallow Hazards

Shallow Water Flows (SWFs) were encountered at some of the wells drilled in the deepwater blocks. Figure 5 below is a picture showing a plume from the shallow flow experienced during drilling operation.

Figure 5
Shallow Water Flow Block 26 Deepwater Trinidad

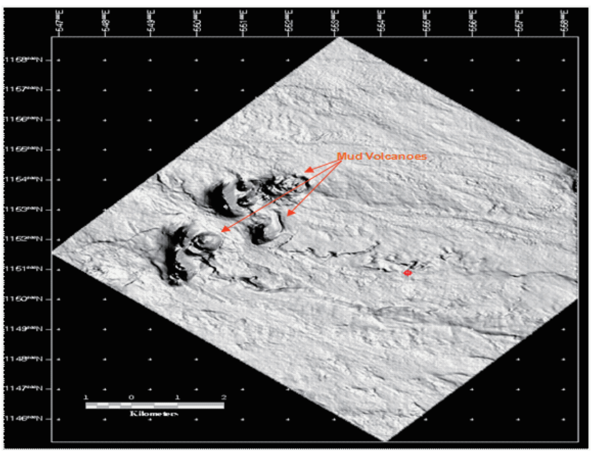

Figure 6
Sea Floor in Block 26 Deepwater Trinidad

The deepwater sea floor is typical of mud volcanoes and seeps (Figure 6). Mud volcanoes are frequently high relief and conical in nature and can range from 165 ft to 7500 ft in diameter and height from 130 ft to 400 ft. Seeps are common on the seafloor and therefore fluid migration pathways are prominent that communicate seeps around the base of some mud volcanoes. These increase the risk of shallow water flows in the deepwater operations. There is also the possibility of gas hydrates in the shallow sediments. This is indicated by a Bottom Stimulating Reflector (BSR). A BSR is a boundary that marks the phase change of water and gas to a solid gas hydrate. A high flux of gas and water through the upper sediments is required to produce a BSR and to produce a concentration of trap gas to pose potential drilling hazards. These conditions are met in deepwater acreages and must be evaluated before drilling. The presence of BSR also suggests that there are sufficient permeabilities in the sediments to be conducive for creating overpressure sands.

Some of the possible mitigations include:

Use shallow seismic surveys and all available offset data to select a location that minimizes shallow sandcontent. Geohazard surveys used to avoid shallow gas (or gas hydrates), can also help select casing setting depths to limit exposure to potential SWF reservoirs in the conductor and surface hole sections.

Well designs should consider that overpressure sands, gassy sediments, and gas hydrates could be encountered when drilling in deepwater Trinidad. Kill weight design should be considered together with mix on the fly capabilities.

Selecting a drill site away from known shallow gas sands increases the chance of drilling success. Learnings from past successes and failures in handling shallow water flows led to the successful installation of 11 slots at one of the most severe shallow water flow problems in the world (Eaton, 1999).

A contingency plan is required for handling gas hydrate formation. Gas hydrates build up were seen in some deepwater wells in Trinidad and therefore a detailed inhibition program should be designed which includes primary and secondary inhibition.

Using an ROV video monitoring of the sea floor around the well head should be a must during drilling. Early detection of shallow water flows that may be encountered could allow sufficient time to initiate corrective action that may prevent damage to, or loss of the well. The rig selected should be equipped with a hot stab glycol line to the connector and the ROV also equipped with glycol pumping capabilities. The ROV is to monitor and report any hydrates build up around the connector. If there are visual indications of ice forming around the connector, the ROV will commence glycol pumping operations. In respect to hydrates, prevention is easier than cure and the possibility of hydrates forming and their implications should be considered during any well control incident.

If feasible, Measurement While Drilling (MWD) logging could be considered for the top hole portion of the well. These logs can be useful in detecting sand units and hence potential SWFs. Also Pressure While Drilling (PWD) tools are capable of measuring annular pressures and detect evidence for shallow water flows while drilling.

3.3 Rig Selection

Rig selection is an important aspect of planning for deepwater and ultra-deepwater drilling. There are several concerns for selection of rigs for deepwater operations in Trinidad. These include high current environment, emergency disconnect capabilities and loop current response time. The rigs used were a semi sub and drill ships. Therefore knowledge of rig motions, station keeping system, riser tensioner system, drift off analysis and ROV deployments are some of the main parameters required for evaluation.

3.3.1 Rig Motion

Knowledge of rig motions is critical when selecting a rig heading in order to minimize weather related downtime. Selection of rig heading depends on the predominant direction of the weather (primary waves and currents) and the resulting rig motions. Typically for offshore Trinidad, the wind and waves come from NE to E direction most of the time. As seen with the movement of the NBC to Trinidad, it is expected that the currents come from SSE to SE direction. This is shown in Figure 7. The wind and wave direction can affect the rig positioning.

For e.g. the normal practice is to head a drill ship into the predominant direction of the current, however this direction can place the waves on the beam and this would not be a desirable position (Figure 7). However, operations might have to be suspended if waves exceeding 8 ft approached the rig on the beam (depending on rig motion operating limit).

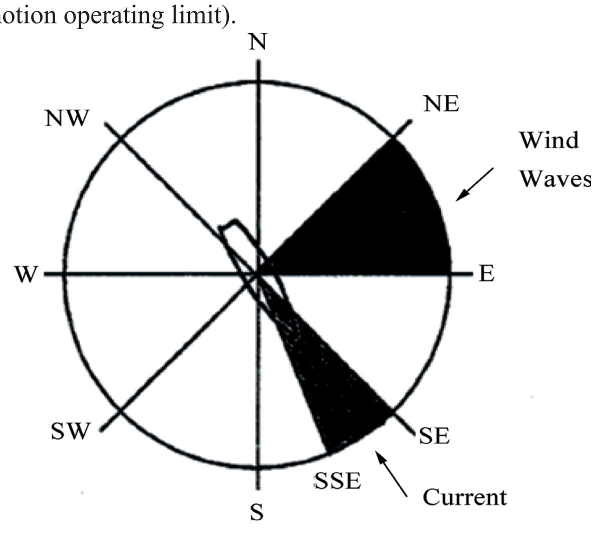

Figure 7
Rig Heading into Current

The estimated weather related downtime for a particular rig can be predicted using typical waves data. For e.g. if a particular month the waves are expected to exceed eight feet 30% of the time then it would be expected to have weather related downtime of 30%. In the example therefore, it is recommended to have the rig heading direction between current and the wind direction (Figure 8). This places the current on the starboard quarter and the wind on the port quarter.

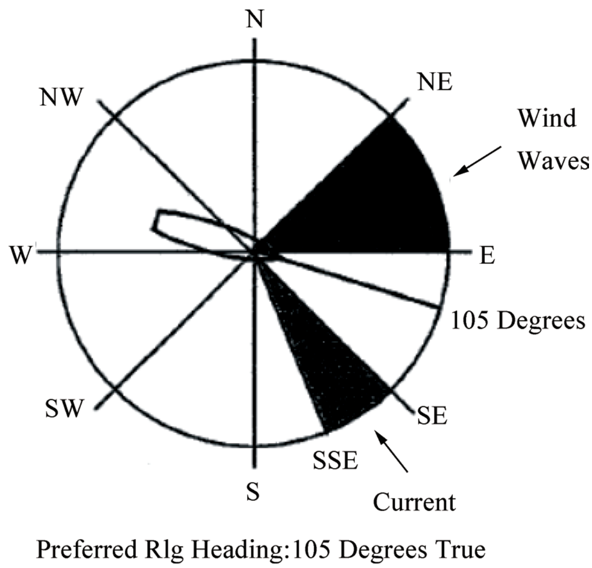

Figure 8
Preferred Rig Heading Based on Rig Motions

3.3.2 Station Keeping Analysis

A station keeping analysis should be done to determine the vessel's capability to maintain station during the operation period, during high winds, waves and currents.

The Dynamic Positioning system should be capable of automatically maintaining position and heading of the vessel within a specified envelope under maximum environmental conditions. The percentage of available thrust required for maintaining station with current and wind/wave approaching from various compass point directions should be evaluated. If the rig does not have sufficient thrust to maintain station in high currents (>3 knots), it may be necessary to suspend operation and rotate the rig to minimize drag on the vessel. Therefore if the thruster is down for repairs or maintenance, key rig personnel should monitor weather conditions and station keeping ability and determine when to suspend operations. It is therefore recommended that a suitable rig be selected with adequate station maintaining capabilities.

3.3.3 Drift off Analysis

During the drilling of one of the deepwater wells, there was an emergency disconnect that caused the detachment of the drilling riser from the wellhead resulting in the discharge of several hundred barrels of synthetic oil based mud on to the seabed near the base of the drillsite. Dynamically positioned vessels occasionally experience unexpected "drift-offs" which occurs if power to the thrusters is lost. As a result the vessel is forced off station by the environment. In order to cope with this unexpected emergency in a systematic manner and prevent damage or loss of the well, watch circles can be established so that key personnel know how to react. For e.g. a yellow watch circle can be established to signal suspension of drilling operations while a red watch circle is a signal to disconnect the drill string and riser from the well. The emergency disconnect sequence is activated. The decision point to initiate the emergency disconnect sequence should be based on the rig's riser tensioner stroke, connector integrity, conductor stress, riser stress, upper and lower flex joint angle and slip joint stroke. The power management system must effectively identify available power and measure consumed power, always maintaining a suitable margin of available power to keep the rig on location. The system must be able to adapt to abrupt changes in power demand such as a sudden storm, an engine drop off line, or the start up of a drilling motor (Shaughnessy, *et al*., 1999).

Selection of fit for purpose deepwater drilling rigs which are especially capable of handling high currents with good positioning capabilities are essential. Having drag reducing riser sleeves and increased riser tensioning capabilities is also important.

3.4 Well Design and Planning

The following are some of the well design and planning issues that need focus:

In the previous deepwater drilling campaign, major drilling problems include well control, lost circulation, stuck pipe and well stability and therefore require substantial pre-drill studies, modeling, and real time adjustments to help mitigate these events.

Well designs and planning should use knowledge based analysis of offset deepwater well data to reduce or eliminate past problems. This can tremendously reduce well cost and therefore encourage more deepwater drilling.

The design of the well should include the drilling of a pilot hole.

The objectives of the pilot hole are:

(1) To identify shallow water flow potential.
(2) To establish hole conditions (pore pressure/hole stability) until the 20" casing depth and beyond if possible.
(3) To optimize 20" casing setting depth with the objective to optimize casing program.
(4) To optimize jetting program (36" structural pile length and jetting parameters).

Most drilling programs should have detailed contingency plans and ability to mobilize any necessary equipment to minimize expensive rig downtime (Shaughnessy, *et al*., 2007). The contingency may involve the following: expandable casing, fishing tools, lost circulation material, extra casing for liners, and storm packers and bridge plugs.

The planning for a relief well must become compulsory and should include rig positioning and surveying. The operator should be responsible for informing the regulatory bodies on the accessibility and availability of drilling rigs to drill relief wells if required.

Rig capabilities should be taken into account when designing a well. Casing size, weight and setting depths are balanced to ensure the rig's capabilities to handle the load (Watson, *et al*.).

According to Rocha *et al*. (2003), a Dynamic Positioning Safety Program (DPPS) is an important program that encouraged drilling contractors as partners in an effort to reduce or eliminate Dynamic Positioning incidents and minimize their effects. Such a program can be looked at, since safety in deepwater drilling must be a priority.

3.4.1 National Oil Spill Contingency Plan

In the past, the oil and gas operators normally stored equipment to handle their own spills at a Tier 1 level. However they will not normally stockpile equipment to manage a Tier 2 or Tier 3 incident within Trinidad and Tobago. Tier One is a discharge occurring at or near a facility as a result of routine operations. Impacts are low and in-house response capability is adequate. Tier Two are medium-sized spills occurring in the vicinity of a facility as a result of a non-routine event. Significant impacts are possible and external (area) support for adequate spill response is required. Tier 3 are large spills occurring either near or remote from a facility as a result of a non-routine event, and requiring substantial resources and support from national or world-wide spill co-operatives to mitigate effects perceived to be wide-reaching, i.e., of national or international significance. There is need for an Oil Spill Response Organization (OSRO) for a spill of a specified quantity of oil within its geographic area. Presently, there are plans for a certified Tier 2 OSRO which is needed before the next phase of deepwater drilling.

Seabed monitoring surveys should be conducted on all wells drilled in the deepwater acreage. Generally, three surveys should be conducted: a pre-drill video survey, post riser and post drill sediment collection surveys. The monitoring surveys should include video observations of the sea floor conditions and a sediment sample collection through the use of an ROV. The purpose of the monitoring surveys is to assess the fate and effects of discharged cuttings at the drillsite location.

In ensuring the effective and efficient execution of deepwater drilling in Trinidad's environment, people management is important. This requires cooperation amongst personnel with diverse technical and cultural backgrounds. Collaborative teams are critical towards success of highly challenging well planning and construction in deepwater and ultra deepwater (Watson, *et al*.).

Proper planning using previous experiences in deepwater will ensure better capabilities for the next period of deepwater drilling in Trinidad.

CONCLUSIONS

Hurricane, waves and currents can have a tremendous impact on deepwater and ultra-deepwater drilling in Trinidad. However the impacts can be minimal if the operator gets access to reliable current measurements and/or forecasts. Historical met-ocean data and daily updates with weekly (and longer) forecasts are available from numerous commercial sources including Ocean Routes and Storm Data. According to the Horizontal Marine Inc. study, the best period to drill deepwater wells in Trinidad is April to June.

Selection of fit for purpose deepwater drilling rigs which are especially capable of handling high currents with good positioning capabilities are essential. Knowledge of rig motions is critical when selecting a rig heading in order to minimize weather related downtime. Selection of rig heading depends on the predominant direction of the waves and currents and the resulting rig motions.

Drilling a pilot hole should be considered before spudding the exploration well. In addition to objectives of the pilot hole mentioned earlier, this hole could be very useful in direct measurements of formation pore pressure and fracture gradients. Also it can give useful data on naturally occurring gas hydrates which are potential future source of natural gas.

Good well design and planning is the key to success in deepwater and ultra deepwater drilling in Trinidad. Analysis of offset deepwater well data and identifying solutions to potential problems must be done in pre-drill planning.

There is need to have a Tier 2 OSRO set up before the next phase of deepwater drilling in Trinidad and Tobago.

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Developing Expert Scenarios Facing Iran's Petroleum Industry

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Abstract

This research discusses future development of Iran's petroleum industry by using strategic management approaches relying on scenario-based planning models. The theoretical frame of this research is a normative paradigm in upper range documents advocate approach. Delphi methods, cross-impact analysis, and scenario-based planning have offered flexible and comprehensive planning combinations in proposing new styles in foresighting products development. In addition, Micmac software was employed to analyze dates. In this research, 235 influencing factors on a product development trend were selected using a PESTEL model and a Delphi approach, then the effects of these factors on each other were tested that eventually 22 key factors were selected. Among 22 key factors, 2 main factors including "political relations" and "the government's dependence on petroleum" were selected using a cross-impact analysis. After that, a 2×2 matrix was formed that contains four scenarios including a playful rabbit, a runaway snake, a noble horse, and a sleeping lion. This research can enhance decision making abilities of top managers through identifying key signals of how each scenario appear in future of Iran's petroleum industry. Results show that management team of petroleum products requires serious etiology and attitude rehabilitation.

Key words: Futurology; Scenario planning; Iran's petroleum products; Key factors; PESTEL model; Micmac software

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INTRODUCTION

Energy is one of the major inputs for the economic development of any country. In case of developing countries, the energy sector assumes a critical importance in view of the ever-increasing energy needs requiring huge investments to meet them. Investment banking firms are intermediaries that can fund energy sectors. They advise firms, distribute securities, and take principal positions in a market[1].

Energy can be classified into several categories based on the following criteria:

- Primary and secondary energies
- Commercial and non-commercial energies
- Renewable and non-renewable energies

(1) Primary and Secondary Energy Sources

Primary energy sources are those that are either found or stored in nature. Common primary energy sources are coal, oil, natural gas, and biomass (such as wood). Other primary energy sources include nuclear energy from radioactive substances, thermal energy stored in earth's interior, and potential energy due to earth's gravity. The major primary and secondary energy sources are shown in Figure 1.

Primary energy sources are mostly converted into secondary energy sources in industrial utilities; for example coal, oil, or gas are converted into steam and electricity.

Primary energy can also be used directly. Some energy sources have non-energy uses, for example coal or natural gas can be used as a feedstock in fertilizer plants.

(2) Commercial Energy and Non-Commercial Energy

(a) Commercial Energy

The energy sources that are available in the market for a definite price are known as a commercial energy. By far the most important forms of a commercial energy are electricity, coal, and refined petroleum products.

(b) Non-Commercial Energy

The energy sources that are not available in the commercial market for a price are classified as a non-commercial energy. Non-commercial energy sources include fuels such as firewood, cattle dung, and agricultural wastes which are traditionally gathered and not bought at a price used especially in rural households. These are also called traditional fuels. A Non-commercial energy is often ignored in energy accounting.

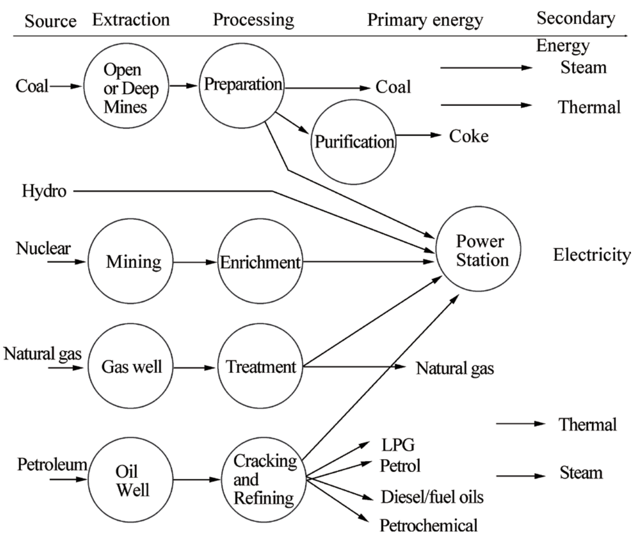


Figure 1
Major Primary and Secondary Sources

(3) Renewable and Non-Renewable Energy

Renewable energy is the energy obtained from sources that are essentially inexhaustible. Examples of renewable resources include wind power, solar power, geothermal energy, tidal power, and hydroelectric power (See Figure 2). The most important feature of renewable energy is that it can be harnessed without the release of harmful pollutants. Non-renewable energy is the conventional fossil fuels such as coal, oil, and gas, which are likely to deplete with time.

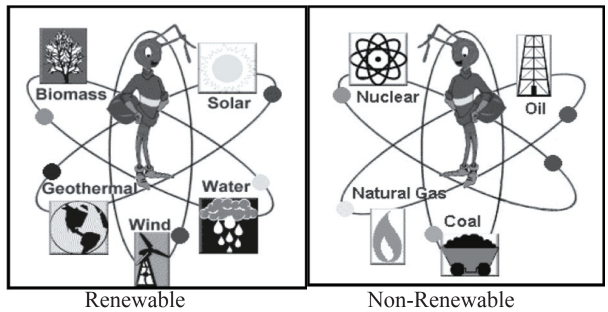


Figure 2
Renewable and Non-Renewable Energies

While several electronic systems including internet have changed the communication world and given particular opportunities to communication ways[10], oil products can be arranged in different categories according to their usage. Therefore, the research results can be used for Iranian petroleum top decision maker in order to lead future production of petroleum products.

One of the most reliable predictions[16] about oil and gas resources shows through the year 2030, that traditional fossil fuels will continue to supply the vast majority of energy needs. At the projected growth rates, both oil and gas will represent about 60% of total energy usage, which is near the share they act today. Nuclear, hydro power, wind, biomass, and other renewable fuels will grow in total at 1.6% annually. The following graphic in the ExxonMobil Outlook depicts its view of the demand for energy globally. (Figure 3 The Outlook's graphics are in color; the parenthetical caption appearing below the graphic as explanation has been rewritten for readers viewing this graphic in black and white copy.)

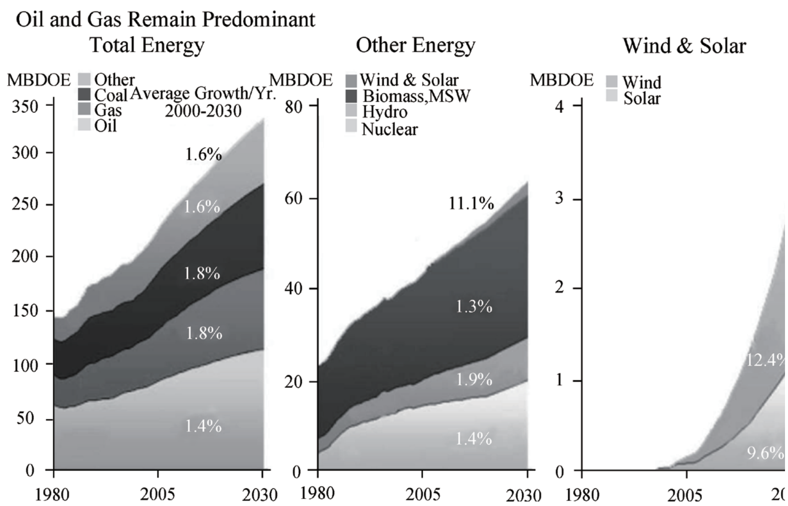


Figure 3
Oil and Gas Resources Until 2030

1. WHAT IS SCENARIO PLANNING: THE REASON TO USE THIS APPROACH

Scenario planning was formed in U.S. Army during the Second World War in order to deal with probable attacks of enemies. After the second World War, Pier Walk and Herman Cain used Scenario planning in Royal Dutch Company in order to influence the decision makers of the company which resulted in remarkable achievements[14]. Strategic planning is a suitable tool to reach organizational goals[15].

There are many different approaches to scenario planning, but most of those presented here are derived from the qualitative approach of Shell/SRI International and share many features[4, 5, 19, 20, 21, 23, 24, 25, 26].

These approaches differ in emphasis due to their variation in goals of the ones who have created them. The research approach to scenario planning is similar to these approaches while it is influenced by adaptive environmental assessment and management[11]. The fast-changing nature of the modern business environment means that planning should be a continuous[12]. In this complex and turbulent environment, relying solely on strategic planning cannot guarantee the success of businesses; rather businesses have to prepare themselves to react to a wide range of probable futures[9]. Scenario planning is considered as a mixture of six interacting stages. Scientists, managers, policymakers, and other stakeholders explore through series of workshops. It begins with identification of a focal issue or problem. This problem is then used as a focusing device in order to assess the system. The assessment is combined with the focal problem to identify key alternatives. Alternatives are then developed into actual scenarios which are tested in a variety of ways before being used in a screened policy. Although this overview presents scenario planning as a linear process, it is often more iterative: system assessment leads to redefinition of the central question, and testing can reveal blind spots that require more assessment[8].

Scenario Planning is a technique that allows for an effective assessment of uncertainty. Figure 4 illustrates the relative position of forecasting (F), and scenarios in terms of value compared to distance into the future[24]. On a short-term period, the environment is highly predictable and forecasting is expected to render high yields. In a very long-term period, uncertainty is so high that strategic planning will render smaller returns. In between, scenario planning provides value; allowing both certain uncertainty and still building upon predetermined knowledge. Next, a description is given of how scenario planning aids companies towards this "break-even-point".

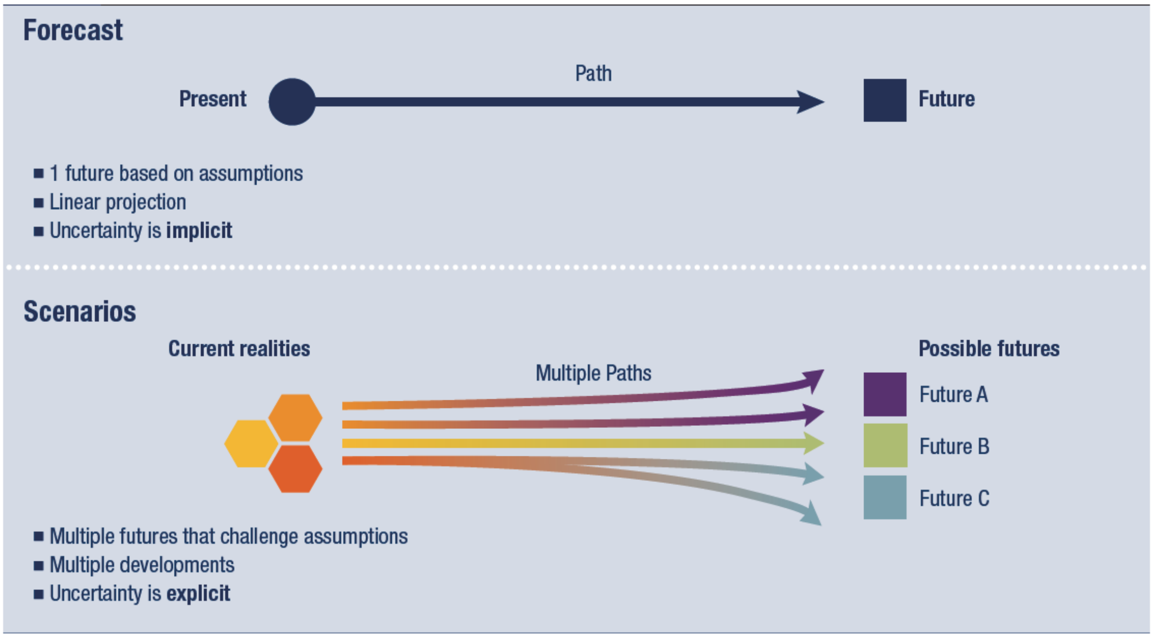


Figure 4
Forecasting Versus Scenario Planning Source: World Economic Forum

1.1 Scenario Planning-Certain Uncertainty

Over the last decades, a scenario planning method has gained popularity. As a business environment is becoming increasingly volatile, the "complexity view" emerged. The "complexity view" suggests that it is fundamentally impossible to predict aspects of the future[24]. Table 1 compares forecasting with scenario planning[7]. The major difference between these two approaches lies in the acceptance of uncertainty and the acting hereupon from a pluralistic ethic.

Table 1
Forecasting Versus Scenario Planning

Forecasting	Scenario planning
Focuses on certainties and disguises uncertainties	Focuses on and legitimizes recognition of uncertainties
Conceals risk	Clarifies risk
Results in single point projections	Results in adaptive understanding
More quantitative than qualitative	More qualitative than quantitative

Schoemaker[20] explains the difference between "traditional" techniques of exploring the future and scenario planning by climbing a mountain: "Suppose you are climbing a mountain. Previous planning would provide you a detailed map describing the constant elements of the terrain. Of course, this traditional planning tool is very valuable and, indeed, indispensable in this case. However, it is incomplete. First, it is a distorted representation (i.e. any two-dimensional map distorts the earth's surface). Second, it ignores the variable elements, such as water, landslides, animals and other hikers." The comparison of Schoemaker points out the value of adding a view that includes important variables to the discussion instead of ignoring them. When climbing mountains, after all, you would at least want to determine what to do when a storm strikes you, or when it starts to rain heavily. As Schwartz[22] states: "To act with confidence, one must be willing to look ahead and consider uncertainties: What challenges could the world present me with?" In relation to Figure 4, the detailed map provides the "predetermined", whilst the assessment of what to do in case of rain enables an assessment of relevant "uncertainties". Scenario planning offers companies the possibility to take charge and proactively deal with different plausible futures. As Ogilvy[25] states: "We need to go towards a way of viewing the world from multiple perspectives…." Since the environment changes, your business should evolve as well.

Without this effort, "there is a lack of understanding of how the wider environment is impacting customers, their needs, and value systems. One cannot stick to one business method of excellence and expect it to be "a winner" in all periods. "Winning means changing the way one plays over time". As important variables in the environment change, strategic plans should as well. For this reason, scenario planning is a continuous process – inducing constant adaptation and learning. Only when we keep learning, we keep looking ahead instead of looking backwards. Learning takes an important place in the scenario planning technique. Van der Heijden[24] considers: "In a world of constant and ever-increasing change, is it sufficient to learn reactively, or is it necessary to learn proactively?" The answer is: the latter. We must find a means to learn "proactively". "Learning is a process of adaptation to one's environment, a process of trial and error, a process of perpetual innovation (metaphorical mutation) followed by a selection of what is most fitting to a particular environmental niche, a process of testing the affordances of different niches and differentially reproducing those innovations which the niche can best afford"[25]. The traditional learning method is one of "single-loop learning". Here, a strategy is predetermined and executed, without adaptations made along the way. "With double loop learning, operating procedures are changed in responsive to emerging situations"[24]. As a result, a company and its employees can effectively adapt to changes in the environment. In Figure 5, double-loop learning is graphically depicted. Double-loop learning enables an effective assessment of uncertainty instead of ignoring it. The underlying assumptions that lead to the strategy formulation are assessed with due regard to external (potential) developments, strategies are kept relevant and up-to-date. In the execution of double-loop-learning, "The key is for organizations to evaluate managers based on good decision processes rather than good outcomes"[24]. This way, assessing past strategies in new situations is stimulated.

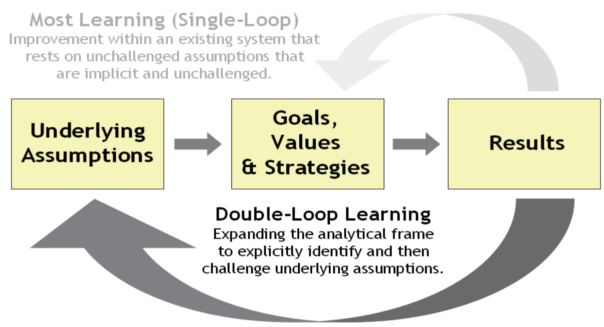


Figure 5
Single-Loop and Double-Loop Learning, Argyris C, Schön D.[3]

Van der Heijden[24] distinguishes the following specific benefits of scenario planning: "Enhanced perception, integration of corporate planning, making people think, structure for dealing with uncertainty, a communications tool, and finally a management tool. Although these concepts mostly speak for themselves, it is useful to develop a more thorough understanding of their meaning in business." First, "Scenarios are … the most powerful vehicles I know for challenging our "mental models" about the world, and lifting the "blinders" that limit our creativity and resourcefulness."[22]. Accordingly, our perception of the external environment and the potential of acting hereupon are enhanced. The knowledge gained, can then be used in a better integration of corporate planning. Evidently, scenario planning also serves as a means to making people think. When stimulated properly in a team environment, people will be likely to actively engage in (strategic) discussion with each other. It is important to: "Make explicit our own tacit understandings and our own cultural insensitivities at the most basic level"[24]. Last, scenario planning is both a good communication tool; for instance to warn people about potential changes, and a good management tool; as a basis for strategic decision making. Here, "a scenario is a tool for ordering one's perceptions about alternative future environments in which one's decision may be played out"[22].

2. OUTCOMES OF SCENARIO PLANNING

Many of the definitions here do not explicitly state the outcome variables of scenario planning; they rather indicate that some authors are unsure about the aims of their definitions. This also suggests that scenario planning professionals are just beginning to consider the importance of defining what they do and explicitly stating what they intend to achieve by doing it. Table 2 shows that almost half of the available definitions date from 1997 to the present. Such a surge of publication activity related to scenario planning suggests a recent increased use of this strategic tool. The first available definition of scenario planning is offered in 1985, yet the process has been applied in practice since the 1960s. The increase in a recent scholarly literature around scenario planning suggests that the process is developing and maturing with the help of professionals. These professionals state that scenario planning does not suffer the same inadequacies and criticisms which have been leveled against general strategic planning processes.

Table 2
Scenario Planning Definitions and Outcome Variables

Author	Date	Definition	Dependent variables
Porter	1985	"An internally consistent view of what the future might turn out to be not a forecast, but one possible future outcome" (pp.63)	A view of one possible future outcome
Schwartz	1991	"A tool for ordering one's perceptions about alternative future environments in which one's decisions might be played out" (pp.45)	Ordered perceptions about alternative future decision making environments
Simpson	1992	"The process of constructing alternate futures of a business' external environment" (pp.10)	Constructed alternate futures
Bloom and Menefee	1994	"A description of a possible or probable future" (pp.223)	A described possible or probable future
Collyns	1994	"An imaginative leap into the future" (pp.275)	An imagined future
Thomas	1994	"Scenario planning is inherently a learning process that challenges the comfortable conventional wisdoms of the organization by focusing attention on how the future may be different from the present" (pp.6)	Challenged comfortable conventional wisdoms about the future
Schoemak er	1995	"A disciplined methodology for imagining possible futures in which organizational decisions may be played out" (pp.25)	Imagined possible decision-making futures
Van der Heijden	1997	(1) External scenarios are "internally consistent and challenging descriptions of possible futures"; (2) an internal scenario is "a causal line of argument, linking an action option with a goal," or "one path through a person's cognitive map" (pp.5)	Descriptions of possible futures; explicit cognitive Maps
De Geus	1997	"Tools for foresight-discussions and documents whose purpose is not a prediction or a plan, but a change in the mind-set of the people who use them" (pp.46)	Changed mind-sets
Ringland	1998	"That part of strategic planning which relates to the tools and technologies for managing the uncertainties of the future" (pp.83)	Managed future uncertainties
Bawden	1998	"Scenario planning is one of a number of foresighting techniques used in the strategic development of organizations, which exploit the remarkable capacity of humans to both imagine and to learn from what is imagined"	Human imagination and learning made explicit
Fahey and Randall	1998	"Scenarios are descriptive narratives of plausible alternative projections of a specific part of the future" (pp.6)	Plausible alternative projections of a specific part of the future
Alexander and Serfass	1998	"Scenario planning is an effective futuring tool that enables planners to examine what is likely and what is unlikely to happen, knowing well that unlikely elements in an organization are those that can determine its relative success" (pp.35)	Examined future likelihoods and unlikelihood
Tucker	1999	"Creating stories of equally plausible futures and planning as though any one could move forward" (pp.70)	Stories of equally plausible futures that inform planning
Kahane	1999	"A series of imaginative but plausible and well-focused stories of the future" (pp.511)	Plausible stories of the future
Kloss	1999	"Scenarios are literally stories about the future that are plausible and based on analysis of the interaction of a number of environmental variables" (pp.73)	Informed, plausible stories about the future
Wilson	2000	"Scenarios are a management tool used to improve the quality of executive decision making and help executives make better, more resilient strategic decisions" (pp.24)	Improved executive strategic decision making
Godet	2001	"A scenario is simply a means to represent a future reality in order to shed light on current action in view of possible and desirable futures" (pp.63)	A represented future reality

3. THE METHODOLOGY AND MODEL

The main purpose of this research is to create scenarios facing Iran petroleum products' development. To do this, as it is shown in Figure 6, basic data on petroleum products were gathered from internal and external resources using a PESTEL framework of Porter. Then a questionnaire was designed with 22 factors and Delphi method was used to collect the required data. After that, following a scenario development model and Micmac software, 4 scenarios were developed.

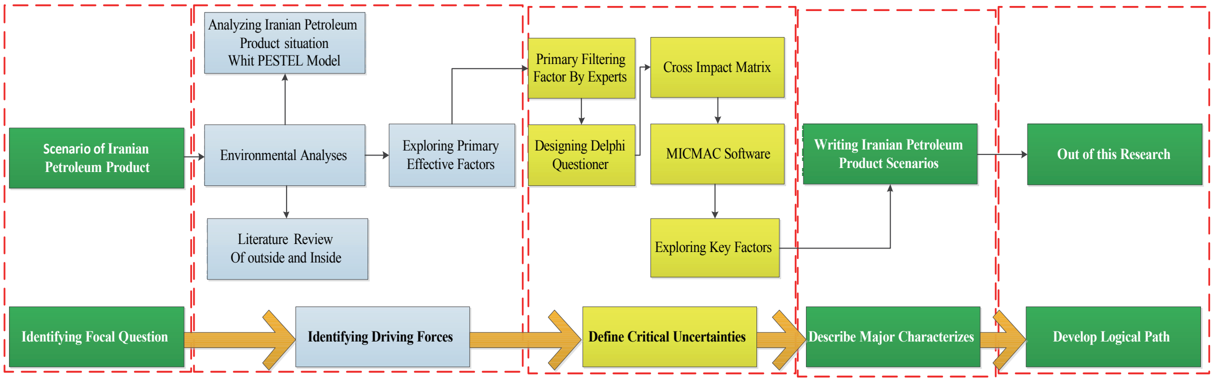


Figure 6
The Research Process

4. THE SCENARIO PLANNING PROCESS

One of the best scenario planning models, which is illustrated as Figure 7, is used to advance the process of this research[2]. This model involves the following steps:

(1) Clarifying the focus of the scenarios (a focal problem)

(2) Identifying future changes and their driving forces

(3) Identifying the critical uncertainties which could lead to distinctly different futures

(4) Fleshing out the major characteristics and development stories for each scenario

(5) Identifying the major implications of scenarios on the organization

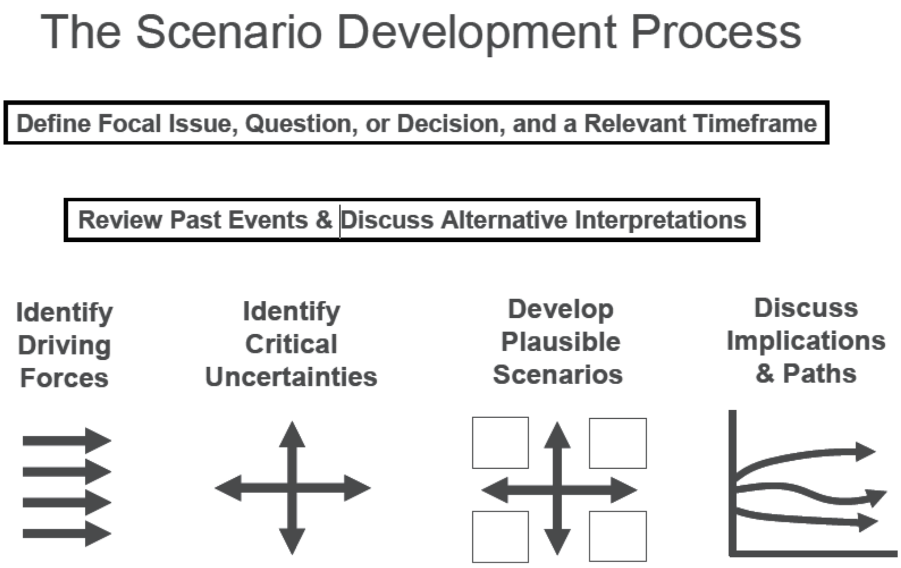


Figure 7
The Scenario Development Process

Developed scenarios provide a context for examining the risks and opportunities associated with different strategic choices or policy options. They become a tool to examine the future consequences of decisions which are made today.

5. BUILDING SCENARIOS

5.1 Step 1: The Focal Problem

Scenario planning begins by identifying a strategic issue. There are an infinite number of stories about the future. The challenge is to focus on those stories that are important. The first step in the process is to agree on the strategic issue we want to address, typically in the form of a "focal" problem. The focal problem ensures that the scenarios are relevant to the strategic issue at hand or to the strategic decision under consideration. Often, the focal problem is informed by interviews at the onset of a project.

5.2 Step 2: Driving Forces

The second step in the scenario planning process is to identify the driving forces of future changes. The scenarios will ultimately be stories describing how different sets of interrelated forces lead to different future outcomes. Identifying the driving forces of the focal problem might involve simply constructing a list. An alternative approach is to pose a question about change.

5.3 Step 3: Critical Uncertainties

The third step in the process is to identify critical uncertainties. Our purpose in building scenarios is to explore the boundaries of uncertainties and to look for a broad range of future outcomes. The emphasis is on divergence not convergence. Some driving forces are more important than others and some are more uncertain than others. Driving forces that have a narrow range of future outcomes are defined as "pre-determined". We need to include them in all the scenarios, but they do not lead to different scenarios.

5.4 Step 4: Scenario Framework, Characteristics, and Storylines

The critical uncertainties may be interpreted as continuums and represented as orthogonal dimensions as shown in Figure 8. Each quadrant represents a unique combination of the critical uncertainties - a 2×2 matrix of possible future outcomes. In today's economic climate, there is an increasing emphasis on cost reduction and increased efficiency[13]. For example, the upper right quadrant defines a future of high carbon costs and the development of disruptive technologies. The scenario question becomes: How does that future come about? What developments need to occur for that future to emerge? What are the major characteristics that would describe this scenario? We have named this scenario Technology Forced. In this way, the logic for 4 distinct but plausible scenarios is established - and the real fun of fleshing out the future begins.

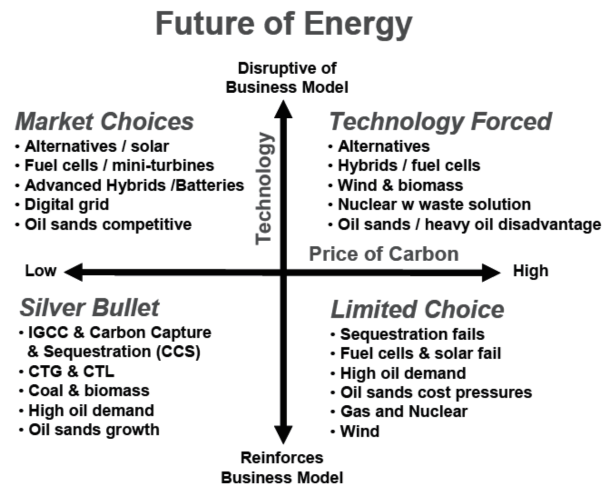


Figure 8
A 2×2 Matrix of Scenario Planning

Having defined a logical framework, involves identifying major characteristics and building a storyline for each scenario. Characteristics are generated in a creative brainstorming session to describe the future end state. The list of driving forces provides a basis for defining the initial set of characteristics. A storyline is then constructed outlining the path from the present to the future. In this way, scenarios are fleshed out into plausible stories of the future. The intent is not to tell "true" stories of the future. The "real" future will likely contain elements of all four scenarios. The goal is to learn from the scenarios, to gain insights on what could change, why it could change and what this knowledge might mean for strategic decisions.

5.5 Step 5: Monitoring the Future

Having developed the scenarios and having made strategic decisions, it is valuable to monitor ongoing change. The scenarios provide a basis for defining signposts for each scenario. Scenario signposts serve as early warning system that signals that a particular scenario is emerging. Watching for these signals allows an organization to make sense of change on an ongoing basis and to react more quickly than competitors to significant changes in the business environment.

6. RESEARCH RESULTS

6.1 Step 1: The Focal Question

The purpose of this step is to determine the focal problem of the research. Utilizing viewpoints of professors and experts of petroleum products scenarios, the problem was appropriately identified. Data and resources used to identify the focal problem were

Iran's perspective document, development plans, and local and international research on petroleum industry, petrochemical industry, and the related industries. The tools of data collection were open interviews and library studies. The output of this step is identifying the focal problem with its important ambiguity, complexity, and significance for the country.

6.2 Step 2: Driving Forces

The purpose of this step is to identify the key factors for creating petroleum products scenarios. Data and resources used to identify the key factors were Iran's perspective document, development plans, and local and international research on petroleum industry, petrochemical industry, and the related industries. The tools of data collection in this step include a Delphi approach, viewpoints of experts, benchmarking, and PESTEL model. Results of this step include an identification of 235 factors in economical areas, political areas, social areas, legal areas, environmental areas, and technological areas that eventually resulted in selecting 22 factors and eventually by expert opinions 2 factors of "political relations" and "the government's dependence on petroleum" were selected for creating scenarios in a 2×2 matrix. These 22 factors are illustrated as Table 3.

Table 3
The Selected Key Factors

No	Areas	Key factors
1	Economical	Dependence of the government's budget on petroleum
2		government non-oil revenues
3		Global demand for oil
4		Discovering new resources
5		using alternative fuels
6		Government economic policies
7	Political	Sanctions and international pressures
8		Adventure of oil producer countries
9		Regional crises
10		Iran's position in the OPEC
11		Iran's foreign policies
12	Social	Local Labor Market conditions
13		Consumption patterns
14		Culture of oil companies
15	Technological	Investment in technological areas
16		Technological complexity
17		Ability of local researchers
18	Environmental	Environmental pollutions
19		Decrease in energy sources
20	Legal	The government laws directly related to the oil field
21		The government laws indirectly related to the oil field
22		International law

6.2.1 Key Factors Influencing the Development of Petroleum Products

As mentioned before, 22 factors were identified as key factors influencing the development of Iran's petroleum products. MicMac software was used to identify these key factors. The cross impact matrix was analyzed in 6 steps using MicMac Software. These steps are as the following respectively:

(1) Systematic perception and observation of the system's stability or lack of stability.
(2) Identifying direct and indirect influences of variables which have the high degree of effectiveness.
(3) Identifying the main factors and using them in scenario planning.
(4) Perception of the whole system and abstinence from trivial analysis.
(5) Identifying the factors that cause instability of the system (factors that should be managed).
(6) Identifying the environment through impact assessment.

Extracting 22 factors, a 22×22 matrix was formed in MicMac Software. The matrix degree of filling was 94/42 percent (Table 4), this shows that the selected factors have high and diffused influence on each other and the system is instable. From 457 assessable relations in this matrix, 27 relations were zero (5%); this means that the factors do not have any influence on each other. Based on the statistical indexes with two data rotation, the matrix has 100% desirability and optimality that shows the high reliability of the questionnaire and the responses.

Table 4
Characteristic of Factors

Indicators	Value
Matrix size	22
Number of iterations	2
Number of zeros	27
Number of ones	68
Number of twos	274
Number of threes	115
Total	457
Fill rate	94.42149%

6.3 Step 3: Critical Uncertainties

In a cross impact matrix, sum of the numbers in rows of each variable shows its influence and sum of the numbers in columns of each variable shows its dependence from other variables. According to the analytical results of this matrix, "political relations" and "the government's dependence on petroleum" have the highest degree of influence and are selected as critical uncertainties factors. Direct, indirect, and potential maps are illustrated in Figures 9 to 13.

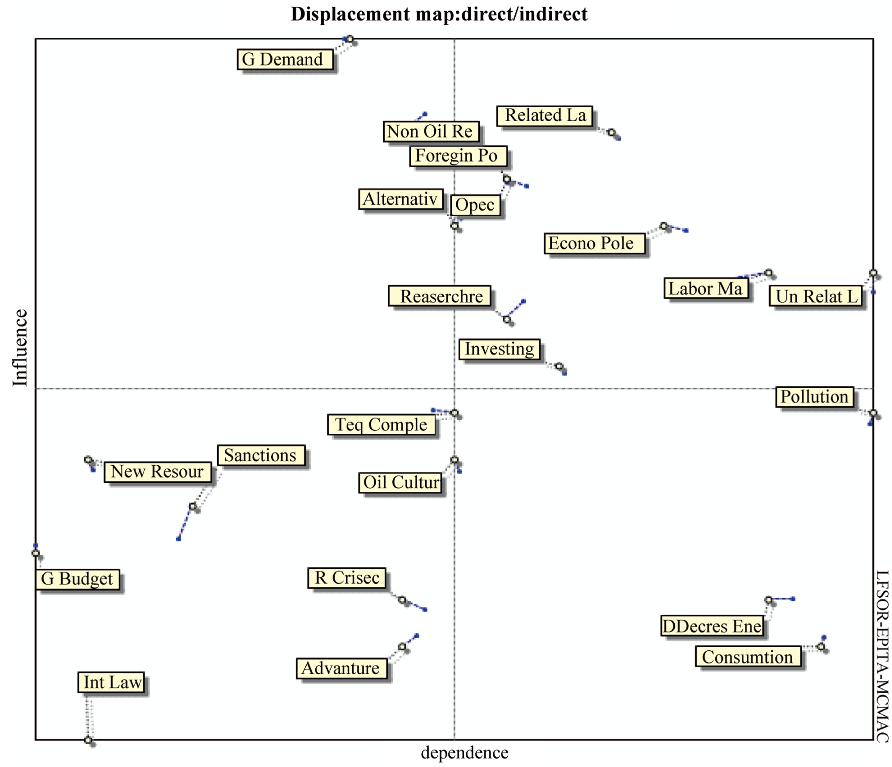
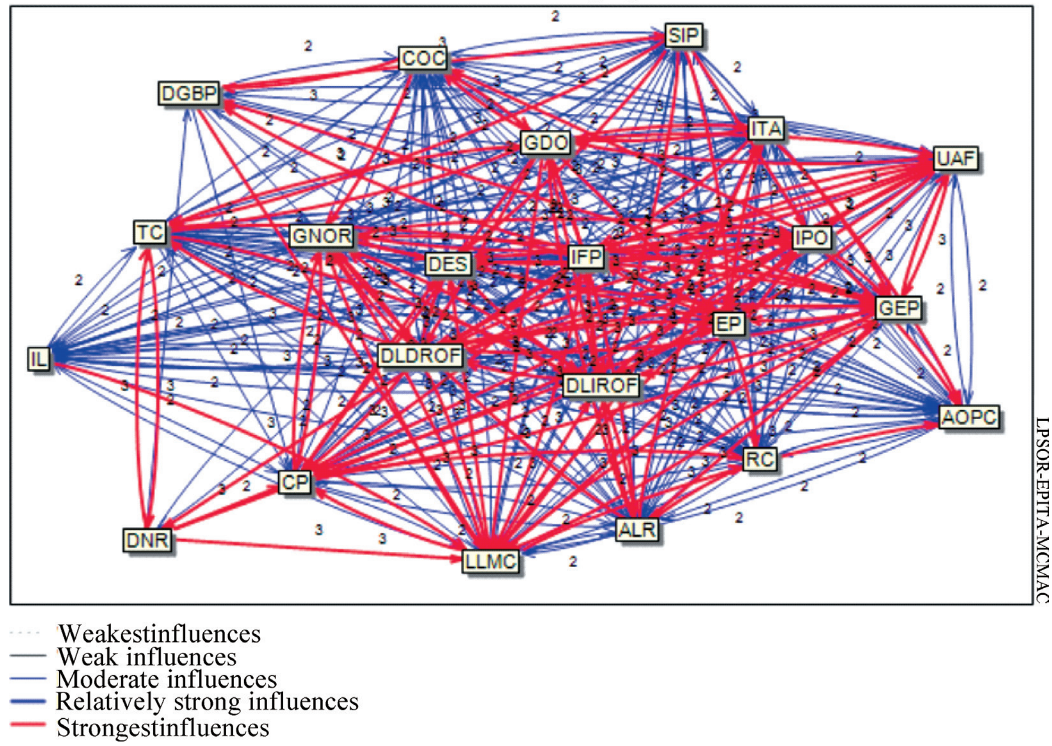


Figure 9
Displacement Map

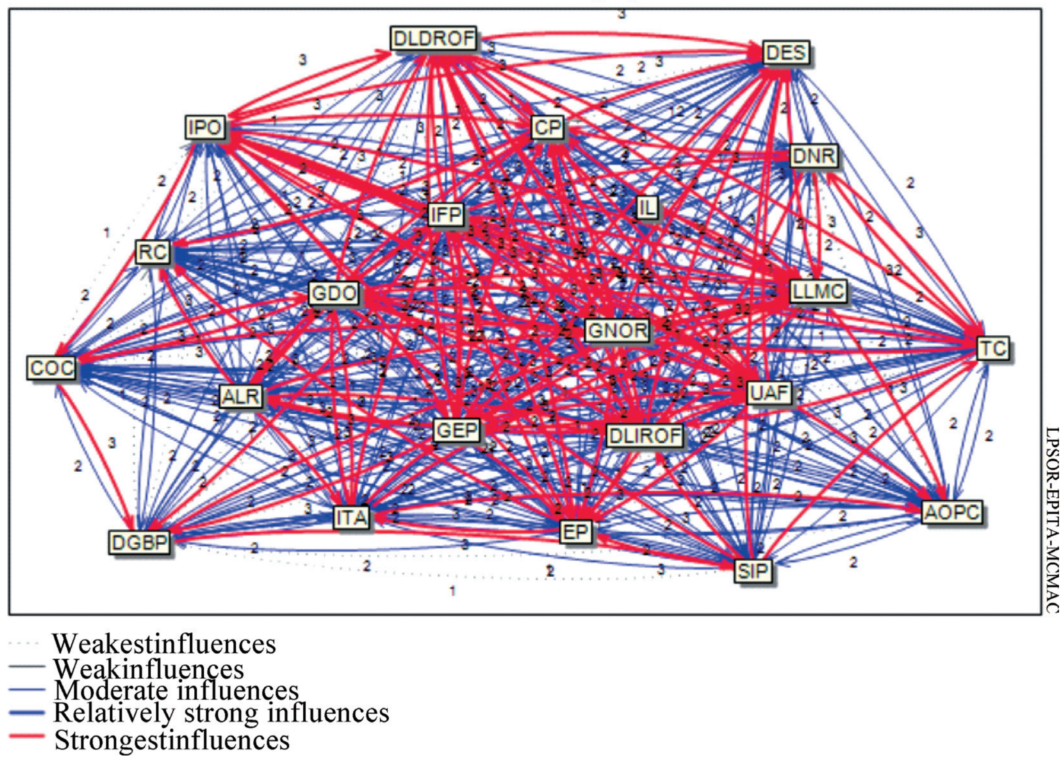
Table 5
Areas, Key Factors, and Their Abbreviations

No	Areas	Key factors	Abbreviation
1	Economical	Dependence of the government's budget on petroleum	DGBP
2		government non-oil revenues	GNOR
3		Global demand for oil	GDO
4		Discovering new resources	DNR
5		using alternative fuels	UAF
6		Government economic policies	GEP
7	Political	Sanctions and international pressures	SIP
8		Adventure of oil producer countries	AOPC
9		Regional crises	RC
10		Iran's position in the OPEC	IPO
11		Iran's foreign policies	IFP
12	Social	Local Labor Market conditions	LLMC
13		Consumption patterns	CP
14		Culture of oil companies	COC
15	Technological	Investment in technological areas	ITA
16		Technological complexity	TC
17		Ability of local researchers	ALR
18	Environmental	Environmental pollutions	EP
19		Decrease in energy sources	DES
20	Legal	The government laws directly related to the oil field	DLDROF
21		The government laws indirectly related to the oil field	DLIROF
22		International law	IL

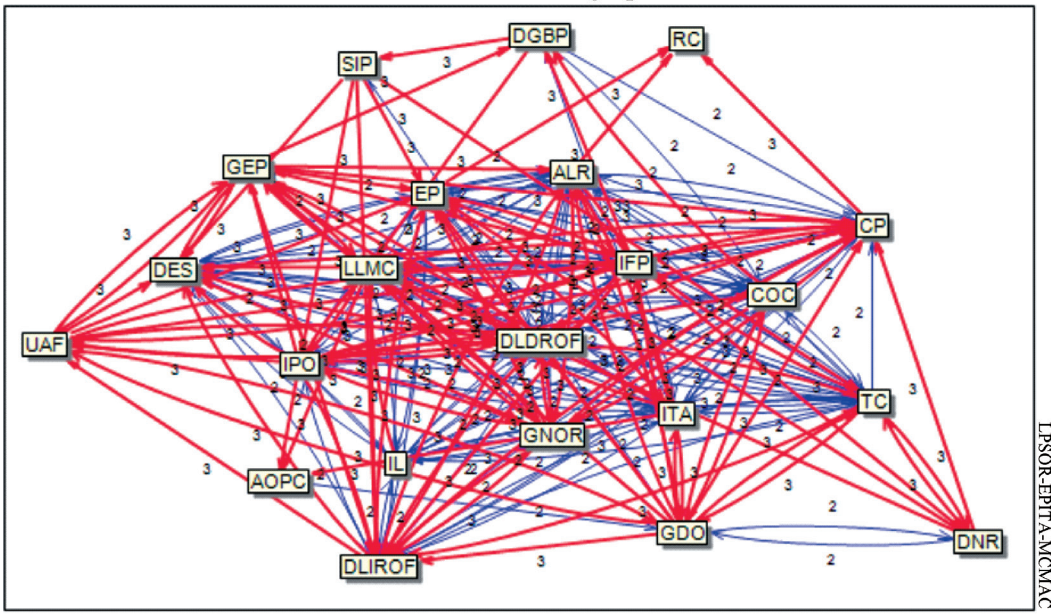
Direct influence graph



Direct influence graph

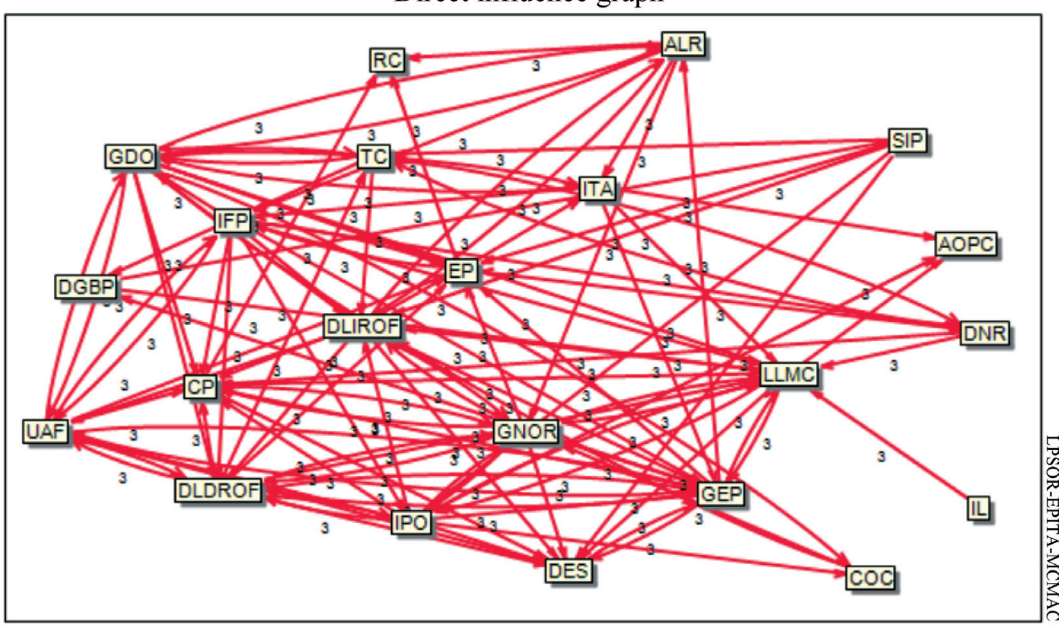


Direct influence graph



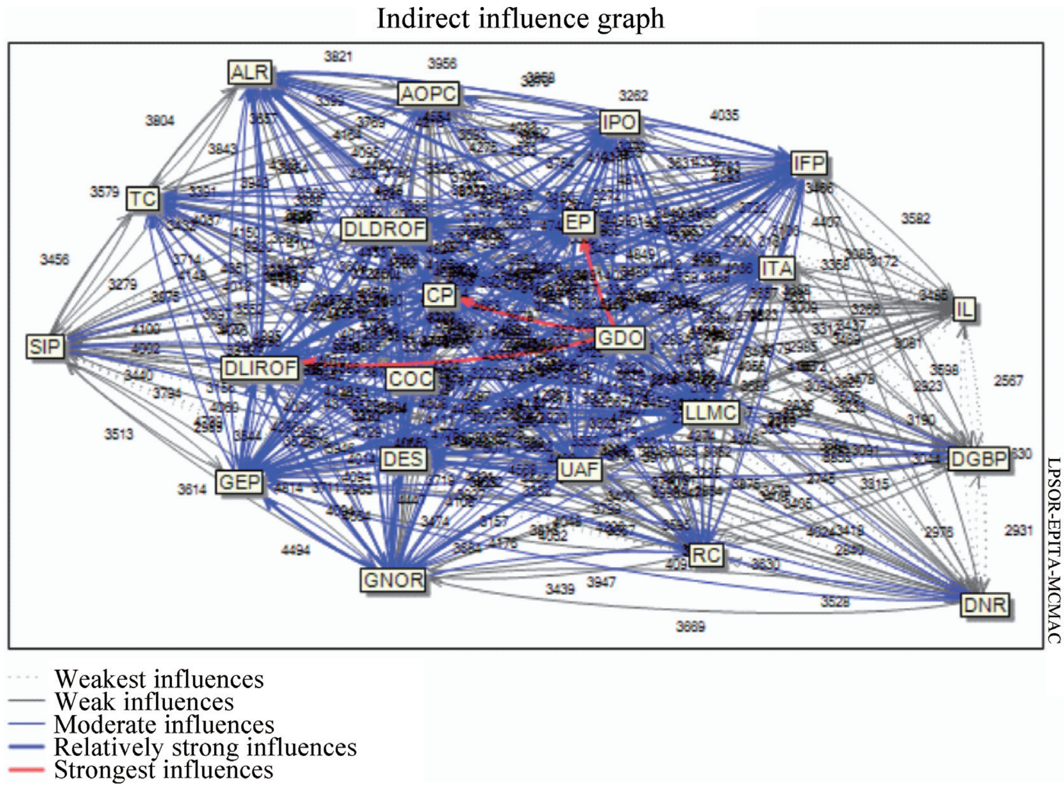
Weakestinfluences
Weak influences
Moderate influences
Relatively strong influences
Strong estinfluences

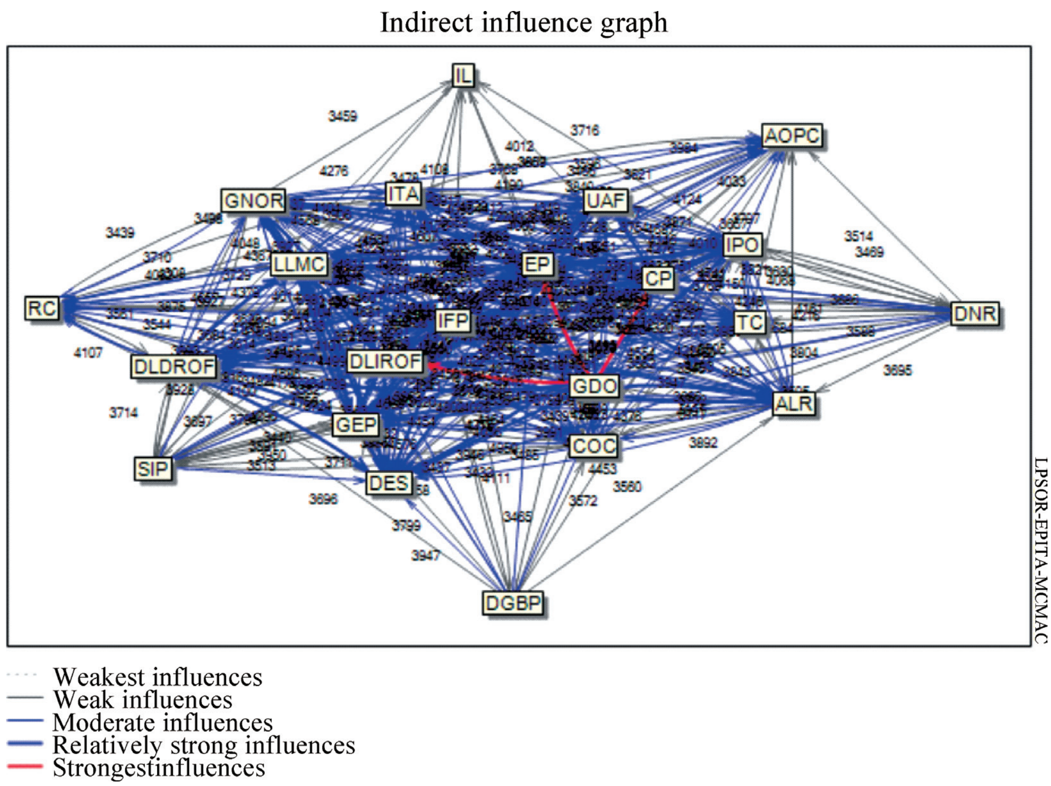
Direct influence graph



Weakestinfluences
Weakinfluences
Moderate influences
Relatively strong influences
Strongest influences

Figure 10
Direct Influence Graphs with Different Influences


Indirect influence graph
ALR
AOPC
IPO
IFP
TC
EP
DLDROF
ITA
CP
IL
SIP
GDO
DLIROF
COC
LLMC
DES
DGBP
GEP
UAF
RC
GNOR
DNR
LPSOR-EPITA-MCMAC
Weakest influences
Weak influences
Moderate influences
Relatively strong influences
Strongest influences


Indirect influence graph
IL
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GNOR
ITA
UAF
IPO
LLMC
EP
CP
RC
IFP
TC
DNR
DLDROF
DLIROF
GDO
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Weakest influences
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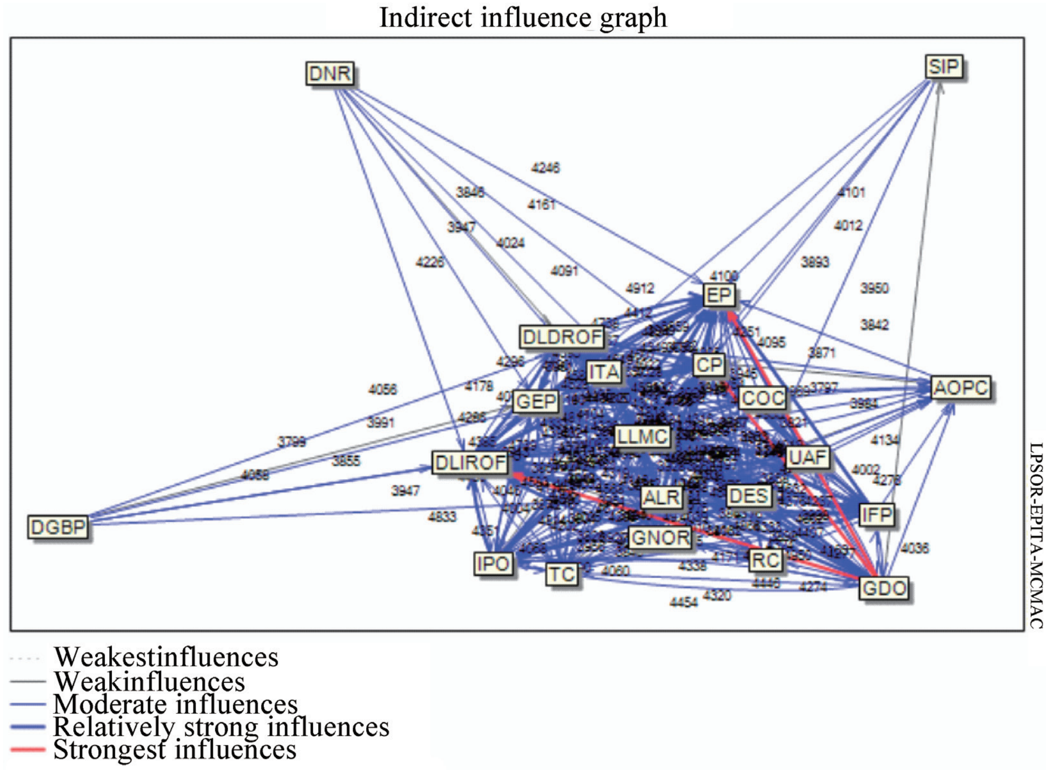


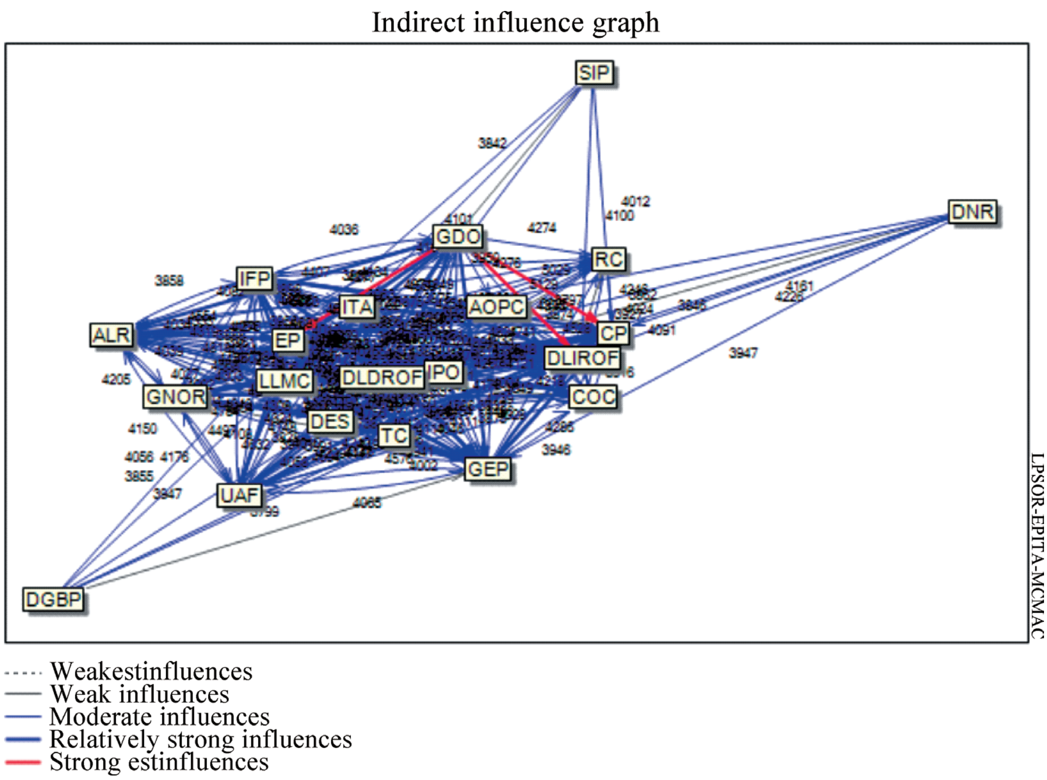
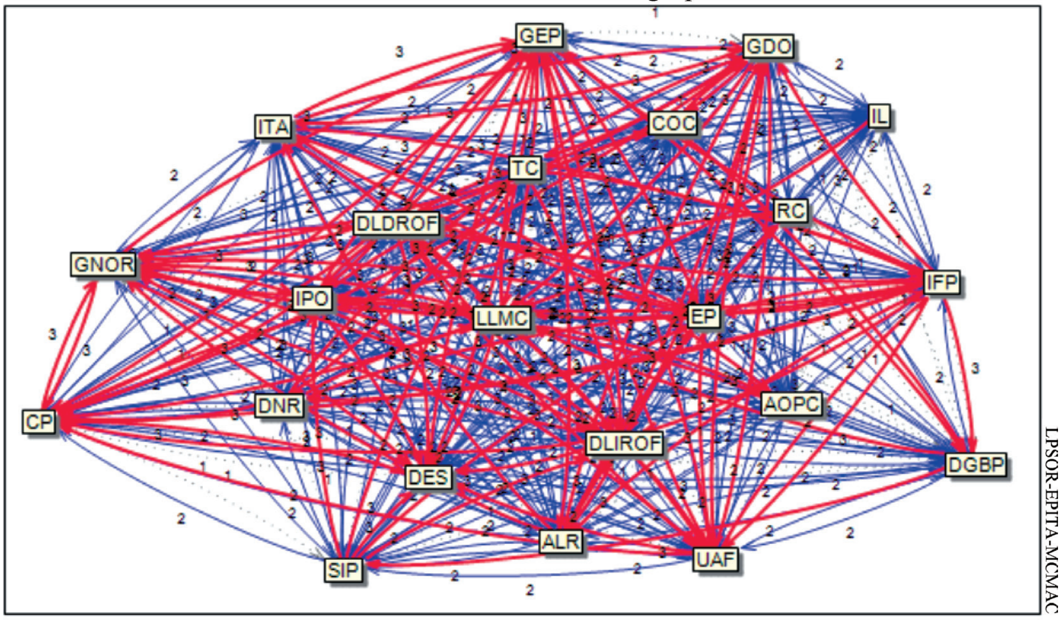


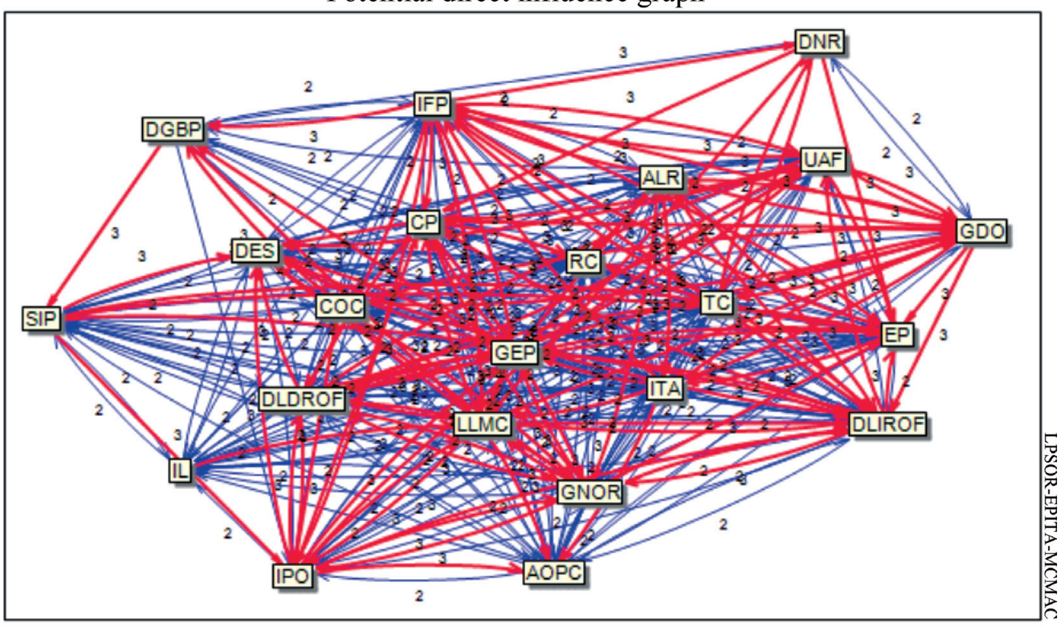
Figure 11
Indirect Influence Graphs with Different Influences

Potential direct influence graph



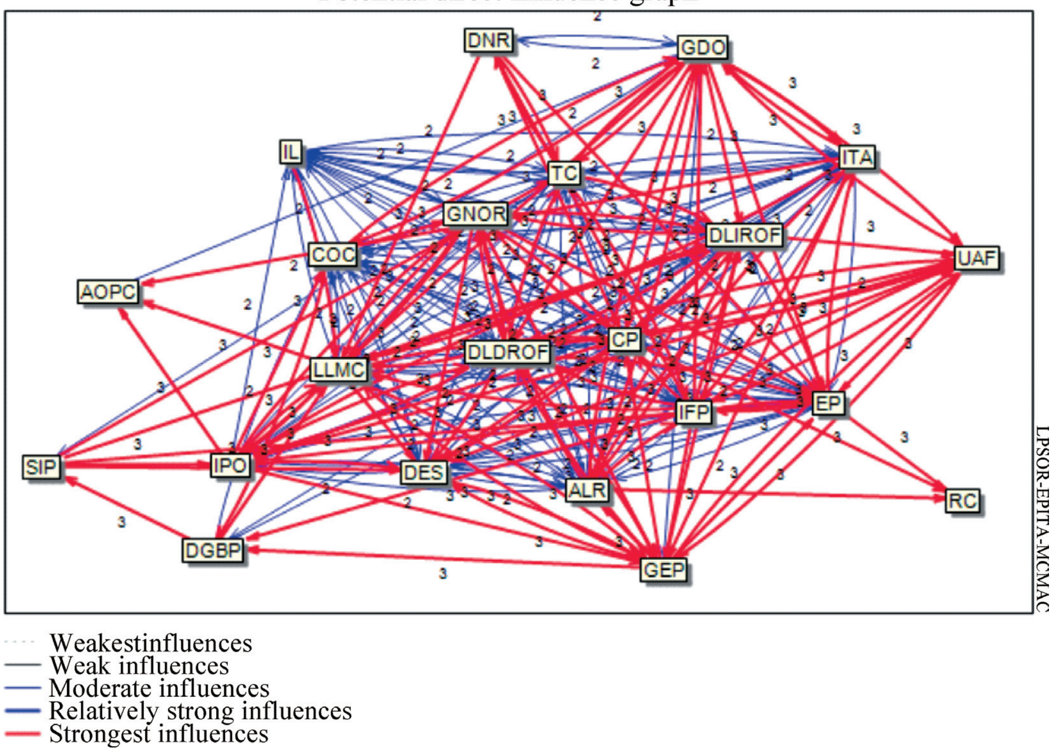
Weakestinfluences
Weak influences
Moderate influences
Relatively strong influences
Strongest influences

Potential direct influence graph



Weakestinfluences
Weak influences
Moderate influences
Relatively strong influences
Strongest influences

Potential direct influence graph



Potential direct influence graph

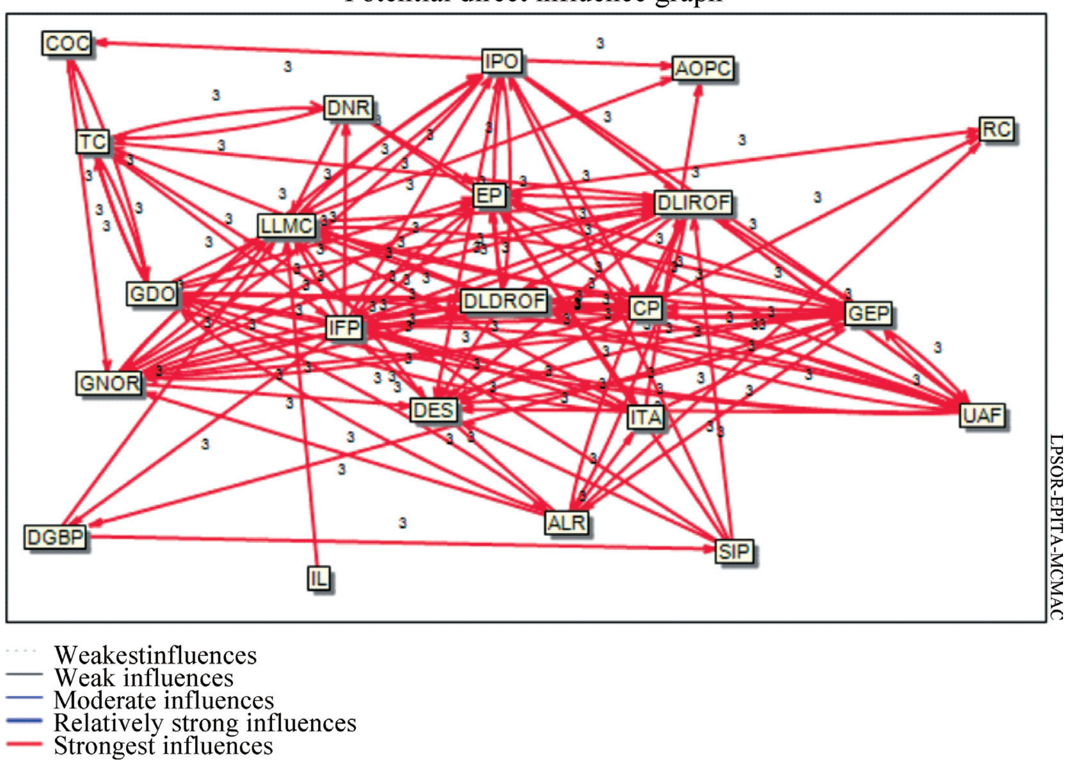
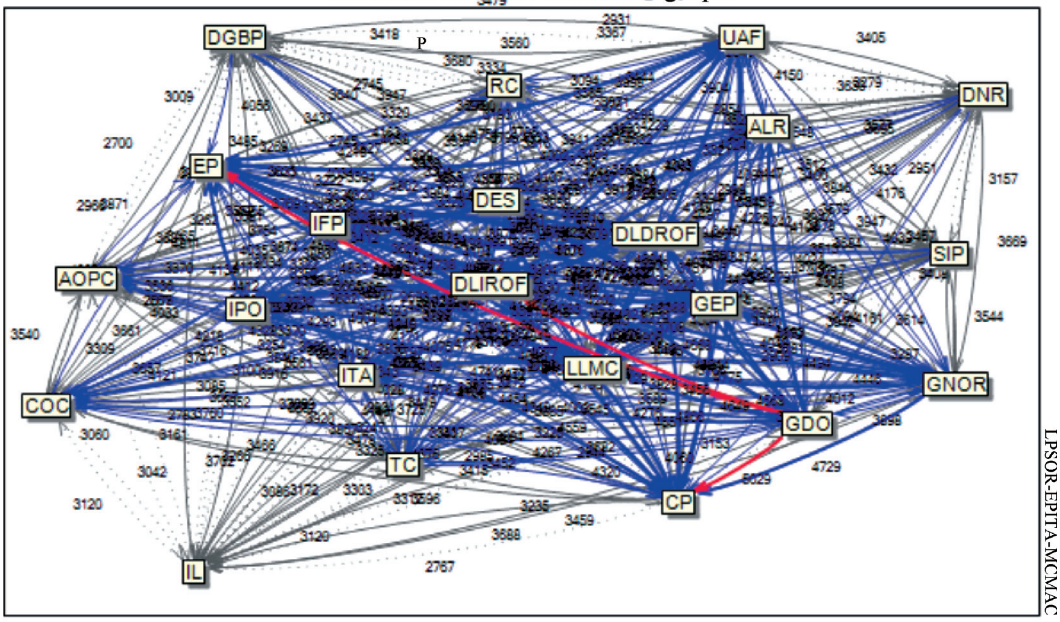


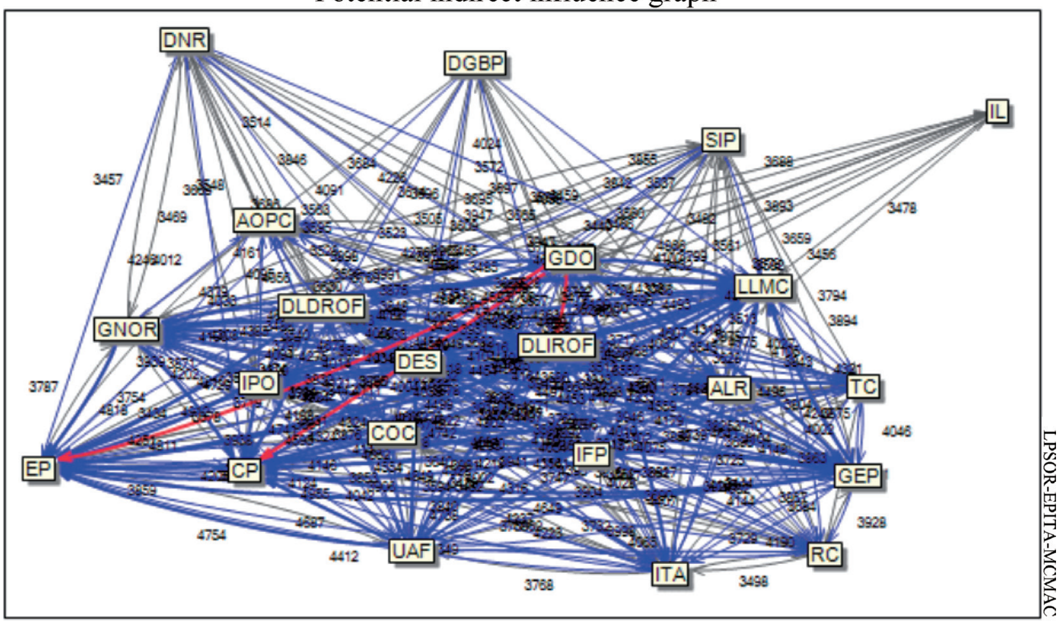
Figure 12
Potential Direct Influence Graphs with Different Influences

Potential indirect influence graph



Weakest influences
Weak influences
Moderate influences
Relatively strong influences
Strongest influences

Potential indirect influence graph



Weakest influences
Weak influences
Moderate influences
Relatively strong influences
Strongest influences

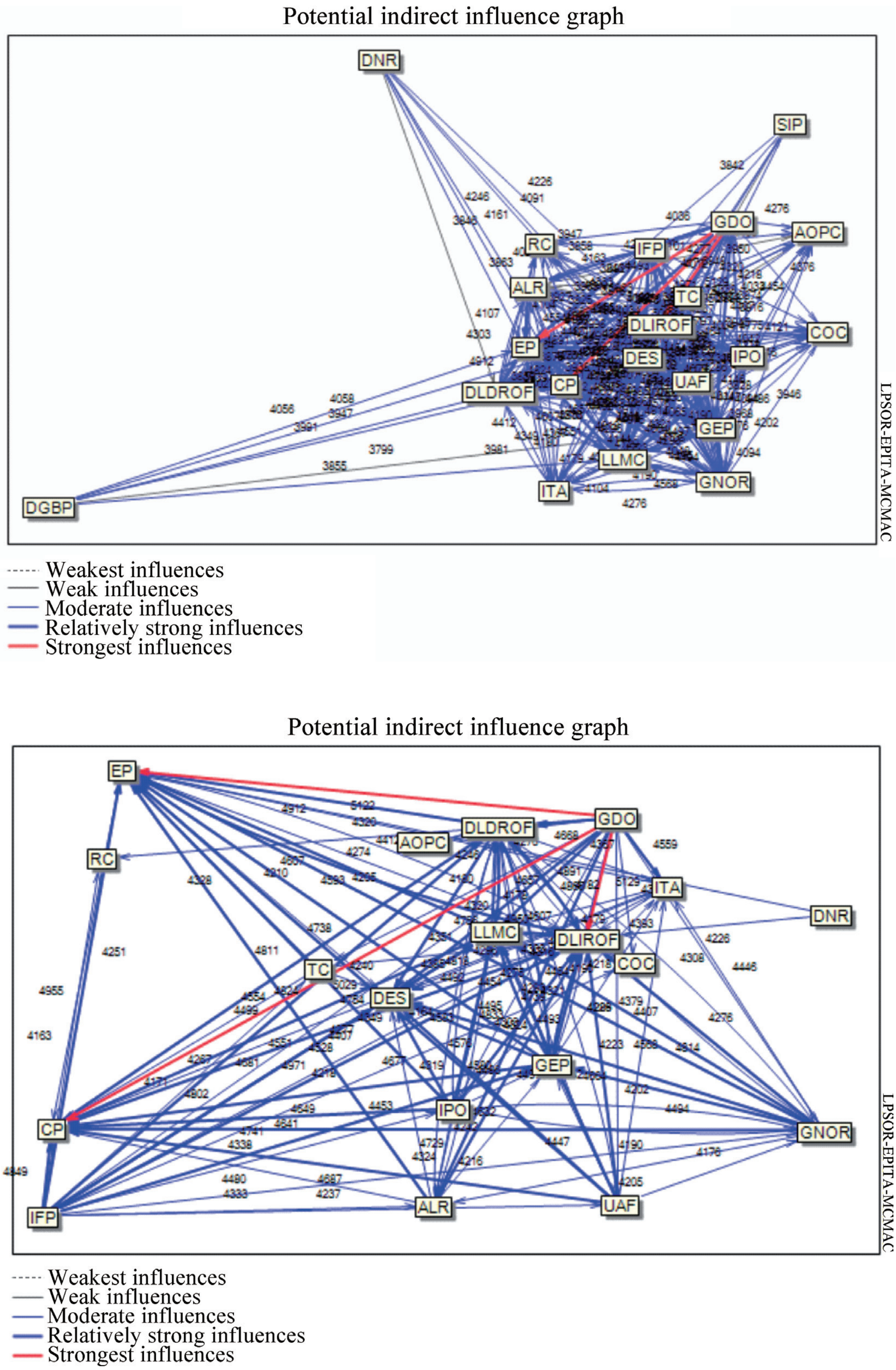


Figure 13
Potential Indirect Influence Graphs with Different Influences

6.4 Step 4: Scenario Framework, Characteristics, and Storylines

Using the identified key factors in previous steps, the purpose of this step is to create scenarios related to petroleum products. In this step, data and resources used to create scenarios are the identified key factors and the upstream documents related to the research area. The tool of data collection is Micmac Software which is used to classify and rank the key factors. According to Table 6, the "political relations" and "the government's dependence on petroleum" Factors have the highest degree of influence. Since the selected factors are general and contain many other factors inside, the accuracy of their selection is confirmed. With regard to classification of factors in the matrix, interaction analysis, and viewpoints of experts and senior managers, political relations and the government's dependence on petroleum forces were selected as key factors for describing scenarios.

Table 6
List of Variables Sorted by Their Influence and Dependence

Classify variables according to their influences

Rank	Variable	Variable
1	3-G Demand	3-G Demand
2	11-Foregin Po	11-Foregin Po
3	20-Non Oil Re	20-Related La
4	2-Non Oil Re	10-Opec
5	10-Opec	2-Non Oil Re
6	5-Alternativ	5-Altermativ
7	6-Econo Pole	6-Econo Pole
8	12-Labor Ma	12-Labor Ma
9	21-Un Relat L	21-Un Relat L
10	17-Reaserchre	17-Reaserchre
11	15-Investing	15-Investing
12	16-Teq Comple	16-Teq Comple
13	18-Pollution	18-Pollution
14	4-New Resour	4-New Resour
15	14-Oil Cultur	14-Oil Cultur
16	7-Sanctions	7-Sanctions
17	1-G Budget	1-G Budget
18	9-R Crisec	19-Decres Ene
19	19-Decres Ene	9-R Crisec
20	8-Advanture	8-Advanture
21	13-Consumtion	13-Consumtion
22	22-Int Law	22-Ilnt Law

LPSOR-EPITA-MICMAC

Classement par depéndance

Rank	Variable	Variable
1	18-Pollution	21-Un Relat L
2	21-Un Relat L	18-Pollution
3	13-Consumtion	13-Consumtion
4	12-Labor Ma	19-Decres Ene
5	19-Decres Ene	12-Labor Ma
6	6-Econo Pole	6-Econo Pole
7	20-Related La	20-Related La
8	15-Investing	15-Investing
9	2-Non Oil Re	2-Non Oil Re
10	10-Opec	17-Reaserchre
11	17-Reaserchre	10-Opec
12	5-Alternativ	5-Alternativ
13	14-Oil Cultur	14-Oil Cultur
14	16-Teq Comple	16-Teq Conple
15	8-Advanture	11-Foregin Po
16	9-R Crisec	9-R Crisec
17	11-Foregin Po	8-Advanture
18	3-G Demand	3-G Demand
19	7-Sanctions	7-Sanctions
20	7-Sanctions	4-New Resour
21	22-Int Law	22-Int Law
22	1-G Budget	1-G Budget

LPSOR-EPITA-MICMAC

Political relations and the government's dependence on petroleum will be exposed to a range of political tensions and irenic political relations whit dependence on petroleum states and independence governments of petroleum (Figure 14).

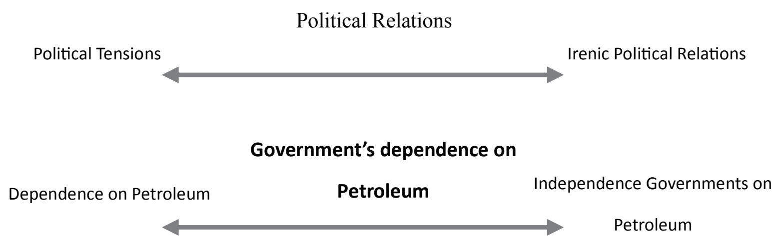


Figure 14
Key Forces Forming a 2×2 Matrix

The role of "political relations" and "the government's dependence on petroleum" forces are shown in Figure 15. As shown in this figure, in the next 40 years (2052), Iran's petroleum product will face 4 scenarios.

After identifying the key factors, a 2×2 matrix was formed as Figure 15, each area of matrix was named, and four scenarios facing Iran's petroleum product was specified. Accordingly, the Figure 15 four scenarios are named as a playful rabbit, a runaway snake, a noble horse, and a sleeping lion.

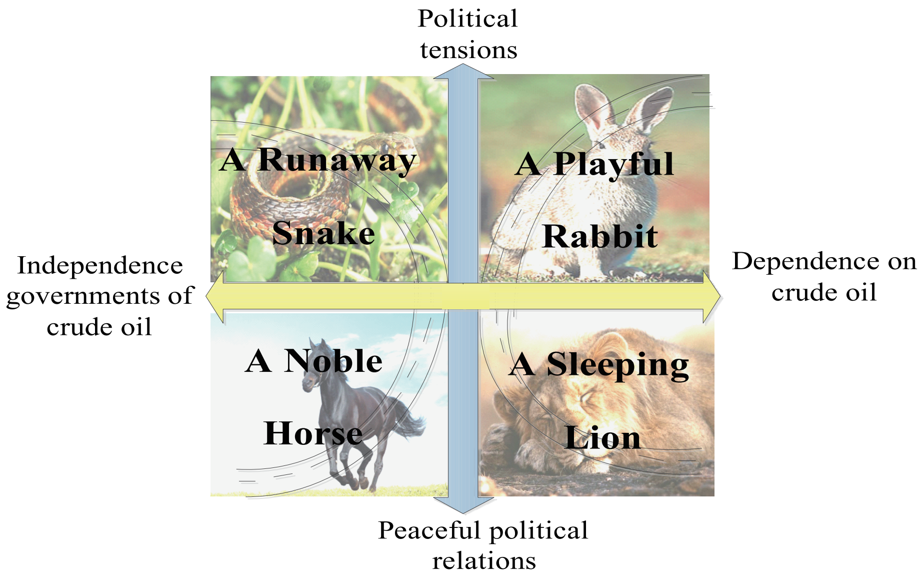


Figure 15
2×2 Matrix of Iran's Petroleum Product Scenarios

7. RESULTS

With regard to the 5-step model, future scenarios for Iran's petroleum Industry are as the following:

7.1 Scenario 1: A Playful Rabbit

In this scenario, there are lots of tensions in Iran's political relations in which governments and the world's major economies severely need the primary sources of petroleum energy in order to reach superpower countries such as China and Russia. As it has rich petroleum resources, benefits from good geographical positions, and dominates the key communication ways, Iran will cooperate strategically with the countries that require its resources and stand against the opposing superpowers. As Iran needs to maintain the support of the allies, it cannot have considerable investments on its petroleum products and should actually act as a resource to nourish these allies. Due to the increased sanctions, international pressures, and decreased exports and non-oil revenues, the government's budget will be severely dependent on selling petroleum products while opposing oil producer countries will increase their predetermined petroleum production in order to decrease Iran's power in OPEC. As a result, Iran would not have any chance to invest in technological areas and will become a sole consumer.

The key factors in occurrence of this scenario are:

(1) High tensions in political relations
(2) High competition to takeover petroleum
(3) An increase in petroleum prices
(4) Low investment in petroleum products
(5) High demand of petroleum in industrial areas and transportation
(6) High dependence of the government's budget on petroleum

7.2 Scenario 2: A Runaway Snake

In this scenario, there are severe tensions among Iran and other countries. As a result of improvements in technological areas, the petroleum demand of these countries will be decreased. Other signs of occurrence of this scenario include technology growth and improvements in environmental pollutions. In this atmosphere, as Iran is not able to attract supports of some countries for the sole purpose of supplying them with petroleum, it will be exposed to a great risk. This is actually an alarming scenario and Iran must invest on its technologies and try to become a power to supply petroleum products. On the other hand, US will do its best to maintain its power and superiority in the current century.

The key factors in occurrence of this scenario are:

(1) High tensions in political relations
(2) The rapid growth of using alternative fuels
(3) The rapid growth of technology
(4) Decrease in oil prices
(5) High demand of petroleum in industrial areas and transportation
(6) Reduced dependence of the government's budget on oil

7.3 Scenario 3: A Noble Horse

In this scenario, Iran's political relations with superpowers are irenic. In this atmosphere, Iran has access to pioneer technologies and is able to guaranty a safe investment in the country. In addition, Iran can decrease its dependence on oil by increasing its non oil-dependent revenues and become one of the main producers of petroleum products.

The key factors in occurrence of this scenario are:

(1) Good political relations
(2) The rapid growth of using alternative fuels

(3) The rapid growth of technology
(4) Decrease in oil prices
(5) High demand of petroleum in business and agriculture
(6) Reduced dependence of the government's budget on oil

7.4 Scenario 4: A Sleeping Lion

This is the best scenario for Iran. The reason is that Iran has the support and dependence of other superpowers on itself. In addition, due to its suitable relations with other countries, Iran is able to access pioneer technologies and attract local and international investors to invest largely on technological areas.

The key factors in occurrence of this scenario are:

(1) Good political relations
(2) Rise in oil prices
(3) High demand of petroleum in business and agriculture
(4) Reduced dependence of the government's budget on oil
(5) High ability to attract capitals and investments
(6) The rapid growth of technology
(7) Increase in non-oil revenues

DISCUSSION

Scenario planning is a process that stimulates imaginative, creative thinking to better prepare an organization for the future. Unlike traditional strategic planning, which assumes that there is usually one best answer to a strategic question, scenario planning entertains multiple possibilities. Unlike contingency planning, which normally focuses on a single uncertainty, scenario planning investigates several uncertainties simultaneously. And unlike simulation modeling, which is heavily numbers-driven, scenario planning involves subjective interpretation as well as objective analysis. For these reasons, we used this technique to create a useful decision making tool, for managing future of Iran's petroleum product which has strategic role in Iran's industry. Although the growth and development of petrochemical industry has been significant and petrochemical production has been doubled after the war between Iran and Iraq, Iran is not on its proper place for petrochemical production now. It should also be mentioned that Iran's share of petrochemical production is less than 0.5 percent in the world and is around 10 percent in the Middle East. If we optimally use available experiences and instruments, plan well in utilizing raw materials, and organize expert human resource under a strong and a dynamic management, it will be possible to promote production levels of petrochemical materials and provide the infrastructure of industrializing the country. According to the results of this research, however, reaching these goals seems to be very difficult. With regard to the analyses as well as the created scenarios, some solutions are provided in order to reach the mentioned goals, Considering that a high volume of fossil fuels are used both in producing petroleum and transportation, it is necessary to pay attention to the alternative energies during the improvement of petroleum products, It is necessary to plan well in reaching Iran's perspectives in petroleum products, Decreasing the production technologies' dependence on other countries and paying attention to limitations and sanction scenarios, Converging the organizations and decision makers of economic and political areas in reaching Iran's perspective and Promoting international credibility and brand.

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Impact of Ultra-Low Interfacial Tension on Enhanced Oil Recovery of Ultra-Low Permeability Reservoir

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Abstract

Ultra-low permeability reservoirs have the characteristics of complex pore throat structure, generally higher injection pressure and lower oil recovery. By means of casting thin sections, pore structure of selected ultra-low permeability core was surveyed. The core was classified into low porosity, low permeability and without natural fractures. Vast majority of throats of the core varied in width from 2.5 μm to 15 μm. Core displacement experiments showed that surfactant flooding could have certain effect of reducing injection pressure and enhancing oil recovery. When interfacial tension was 5.93×10^{-2} mN/m, decompression rate reached 7.65%, and recovery was improved by 4.09%. And when interfacial tension was 4.9×10^{-5} mN/m, decompression rate reached 25%, and recovery was improved by 11.6%. The lower interfacial tension is, the better the effect of reducing injection pressure is, and the higher the extent of enhancing oil recovery is. In general, surfactants have a great application prospect on the oil field development of ultra-low permeability reservoir, and the interfacial tension should be reduced as far as possible.

Key words: Low permeability; Surfactant; Interfacial tension; Emulsion; Enhancing oil recovery

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INTRODUCTION

Ultra-low permeability reservoirs have the main characters of thin pore throats, large specific surface area, low permeability and strongly Jamin effect (Zeng *et al*., 2007). The seepage rule of ultra-low permeability reservoirs does not obey the Darcy's law, and there is a threshold pressure gradient (Zeng *et al*., 2010), which is different from that of middle and high permeable reservoirs (Yin *et al*., 2010). After injecting water, dispersed oil droplets remain in the pores of reservoirs, and cannot pass the minute pores. The oil phase of reservoirs flows by the way of small slugs or drops, instead of continuous flow. When the oil droplets pass narrow throats, the injection pressure rises due to resistance produced by Jamin effect. The water lock is easily formed after oil well operation, and the energy of ultra-low permeability reservoirs spreads slowly. So the displacement pressure of ultra-low permeability reservoirs is usually high, and water flooding is very difficult. Meanwhile, natural energy of ultra-low permeability reservoirs is insufficient. In short, the initial productivity is higher, production declines quickly and the ultimate oil recovery is low.

Surfactants can decrease interfacial tension of oil-water, improve the oil/water seepage characteristics, so reduce injection pressure and enhance oil recovery of ultra-low permeability reservoir. The mechanism of surfactant active mainly includes: reducing interfacial tension of oil-water, altering the wettability of rock surface (Adibhatia & Mohanty, 2007; Bortolotti *et al*., 2010; Seethepalli *et al*., 2004), emulsifying crude oil (Liu *et al*., 2006), increasing the surface charges, conglomerating oil drop, forming oil zone, changing the rheology of crude oil and so on. At present, scholars have done a lot of experimental studies about surfactants improving the development effect of low permeability reservoirs (Adams & Schievelbein, 1987; Sun *et al*., 2009). Manrique *et al*. (2006) found that current water flooding recovery was only 40-50% of the OOIP because of microscopic oil trapping and macroscopic bypassing. Torabzadeh and Handy (2006) found that surfactants could be used with injection fluids to increase recovery efficiency of immiscible displacements through reduction of interfacial tension, and the oil-water relative permeability increased by decreasing interfacial tension at given water saturations. Babadagli (2005) suggested the surfactant injection was recommendable in the pre-waterflooded unfractured zones as long as the proper surfactant type was selected. To use a surfactant solution for tertiary recovery, surfactant concentration, type and interfacial tension were important factors. Liu and Li (2006) found that reducing interfacial tension of oil-water of low permeability reservoirs could reduce additional capillary resistance, and increase relative permeability of water phase. Mohan (2009) studied the feasibility of oil recovery by surfactant flooding from an oil-wet carbonate reservoir. The unique features of the subject reservoir were high salinity and low permeability (2-5×10^{-3} μm^2). 80% OOIP was recovered using the surfactant which gave low interfacial tension (10^{-3} mN/m) in comparison to 60% from water flooding at similar pressure drops.

The study has showed reducing interfacial tension of oil-water is the most important mechanism of enhancing oil recovery (Edin *et al*., 2010), but it is not the only mechanism. Some people think that when interfacial tension is too low and emulsified oils are too small (Berger *et al*., 1988), the sweep efficiency of displacement fluid is not big and the recovery of ultra-low permeability core is not high. But others think that interfacial tension must reduce to 10^{-5} mN/m or even lower if necessary to activate the oils of ultra-low permeability reservoirs.

For ultra-low permeability core, the past study is less effort on the impact of ultra-low interfacial tension of oil-water on injection pressure and enhancing oil recovery. For this reason, in the first place, the distribution of pore structure, especially throats width, was studied by means of casting thin sections of ultra-low permeability core in this paper. Surfactant formulations of different levels of ultra-low interfacial tension were filtered out. The influence of ultra-low interfacial tension on reducing injection pressure and enhancing oil recovery of ultra-low permeability core was studied through the displacement experiments.

1. MATERIAL AND METHODS

1.1 Material

In this study, natural ultra-low permeability core of Shengli Oilfield was used, and formulated surfactants HFYQ-B were selected which contains 30% of active ingredients. We used the formation water of Shengli Oilfield, whose salinity was 1785 mg/L. The simulated oil was obtained by mixing diesel and crude oil of Shengli Oilfield with the proportion of 4:6, and its viscosity was 2.28 mPa·s at 50 °C. Many apparatuses, including TX-500 spinning drop interface tensiometer, reservoir simulation displacement equipment, electronic balance, etc., were applied in the experiments.

1.2 Providing Casting Thin Section

Natural ultra-low permeability core of Shengli oilfield was used to obtain casting thin section. Wash and dry the core, then cut it to get a cylindrical rock thin section whose thickness was about 2mm. The rock thin section was marked as core-1, while the remainder was marked as core-1'. Squeeze the blue organic resins into the rock thin section in condition of a constant vacuum. Polish it to get a casting thin section. Survey the pore structure of the section through a microscope and draw a throat distribution histogram of it.

1.3 Interfacial Tension Test

The surfactant HFYQ-B solutions of different concentrations with the formation water were prepared. Then interfacial tensions between the solutions and the simulated oil were measured by using the spinning drop interfacial tensiometer at 50 °C. The minimum value of dynamic interfacial tension was taken as evaluating indicator (Taylor *et al*., 1990). Surfactant formulations of different levels of ultra-low interfacial tensions were screened out.

1.4 Surfactant Flooding in Low Permeability Core

The basic data of core-1' are listed in Table 1.

Table 1
Basic Data of Core

Core No.	Length, cm	Diameter, cm	Gas log permeability, 10^{-3}μm^2	Water permeability, 10^{-3}μm^2	Pore volume, cm^3	Porosity, %
1'	8.03	2.50	0.52	0.07	4.05	13.5

The core whose gas log permeability was 0.52×10^{-3} μm^2, belonged to ultra-low permeability core. For the core-1', the impacts of ultra-low interfacial tensions of oil-water on reducing injection pressure and enhancing oil recovery were studied through core displacement experiments. Experimental temperature was 50 °C. And the flow chart is shown in Figure 1.

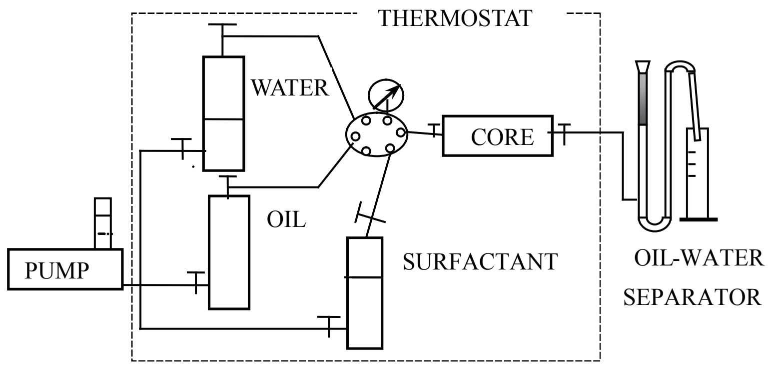


Figure 1
Flow Chart of Core Displacement Experiments

Experiment procedures were as follows:

(1) Weigh the core after drying it, then vacuumize and saturate it with formation water. Weigh again to calculate the pore volume of the core.
(2) Drive the core with formation water at a constant speed of 0.05 mL/min under a temperature of 50 °C.
(3) Drive the core with the simulated oil to irreducible water saturation, age 24 hours, record the volume of oil saturated, and calculate irreducible water saturation.
(4) Drive the core with the formation water at a constant speed of 0.05 mL/min, and stop experiment when water content was more than 98% at the outlet end. In this process, record pressure variation and cumulative oil production, and calculate the recovery of the first water flooding.
(5) Inject surfactant slug of certain interfacial tension into the core at a constant speed of 0.05 mL/min.
(6) The second water flooding was the same to the step (4).
(7) Wash and dry the core. Repeat the steps (1-6) of the experiment through changing interfacial tension of oil-water.

2. RESULTS AND DISCUSSION

2.1 Analyzing Casting Thin Section

The picture of casting thin section of core-1 is shown in Figure 2. Blue represented pore structure of the core.

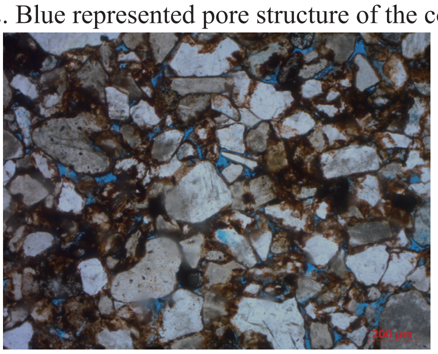


Figure 2
Picture of Casting Thin Section of Core-1

As shown in Figure 2, statistical analysis found that there were 124 pores in the casting thin section of core-1. Among them, there are 86 pores with diameters below 15 μm, 29 pores between 15 and 30 μm, and 7 pores between 30 and 45 μm in diameter, accounting for 69.35%, 23.387% and 5.645% of all the pores respectively. Yet, there are only 2 pores greater than 45 μm in diameter, which is about 1.61% of all the pores. The average pore diameter size is only 27.90 μm. The average ratio of pore to throat size is 0.63, the homogeneity index is 0.58, the sorting coefficients is 12.35, the area percent of pore of core is only 1.12%, and the average coordinate number is 0.35.

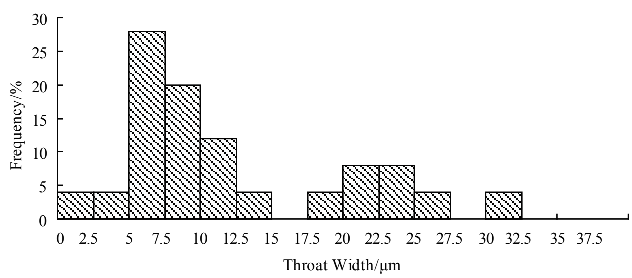


Figure 3
Throat Distribution Histogram of Core-1

The throat distribution histogram of core is shown in Figure 3.

As shown in Figure 3, the vast majority of throats varied in width from 2.5 μm to 15 μm. And only a few throats varied in width from 17.5 μm to 27.5 μm. The largest and the smallest diameter of throats are 30.8 μm and 1.14 μm respectively, and the average diameter is 12.36 μm.

Based on the above analysis, the core was characterized as low porosity, low permeability and without natural fractures.

2.2 Interfacial Tension Test

The interfacial tensions between the solutions and the simulated oil were measured at 50 °C. The relationship curve of interfacial tension with concentration is shown in Figure 4.

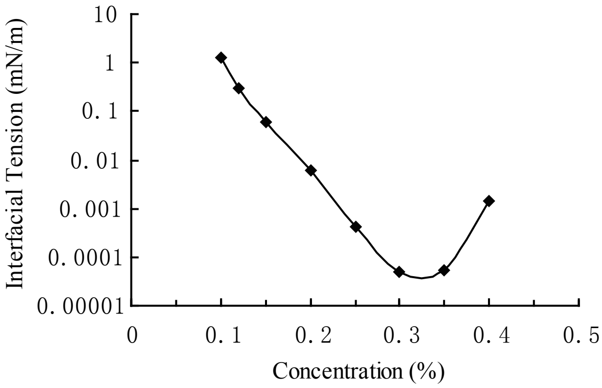


Figure 4
Relationship Curve of Interfacial Tension with Concentration

As can be seen from Figure 4, with increasing HFYQ-B concentration, interfacial tension rapidly decreased at first and then increased. With the concentration increased from 0.3% to 0.35%, interfacial tensions were as low as the order of magnitude of 10^{-5} mN/m. Analyzing its reason, it mainly is that the molecules adsorbing on the interface gradually increase with the increase of surfactant concentration, so the oil-water interfacial tension decreases rapidly. As the concentration of HEYQ-B continues to increase, surfactant molecules tend to be oriented arrangement at oil/water interface. As critical micelle concentrations (CMC) of surfactants in complex system are different, the contents of surfactants are different, and the distribution proportion of surfactants adsorbed at oil/water interface also changes continuously. When the distribution proportion of surfactants reaches a certain value, the interfacial tension reaches its lowest point. As the concentration continues to increase, some surfactants have formed micelles in solution, and adsorptions of the surfactants at the surface are no longer increase. And yet, adsorptions of other surfactants at the surface could still change. Because of the competing adsorption phenomena between the components, the distribution proportion of surfactants adsorbed at oil/water interface continue to change, and no longer remain its optimal value. So the oil/water interfacial tension is rising rather than falling.

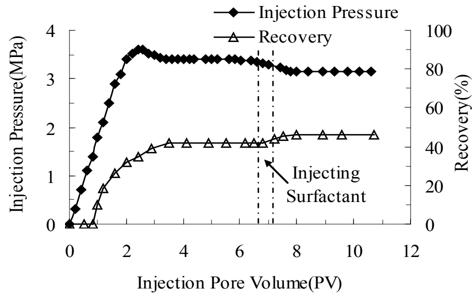
For above results, the surfactant formulations of different levels of ultra-low interfacial tension (10^{-2}-10^{-5} mN/m) are shown in Table 2.

Table 2
Surfactant Formulations of Different Levels of Interfacial Tension

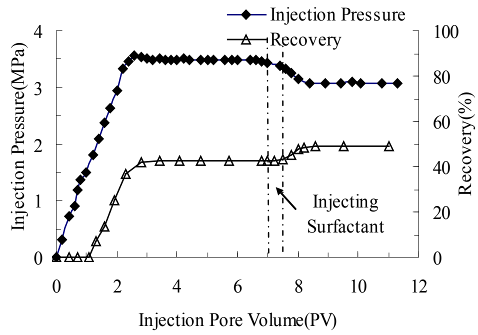
Formulations	Concentrations of surfactant, %	Interfacial tensions, mN/m
1	0.15	0.0593
2	0.20	0.0092
3	0.25	0.00071
4	0.30	0.000049

2.3 Surfactant Flooding in Low Permeability Core

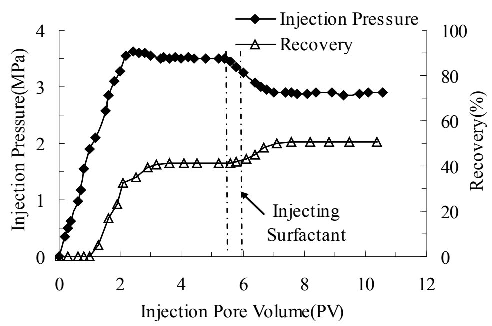
Under different ultra-low interfacial tensions of the selected surfactant formulations, the curves of injection pressure and recovery with injection pore volume in the processes of the first water flooding, injecting surfactant slug and the second water flooding are seen in Figure 5.



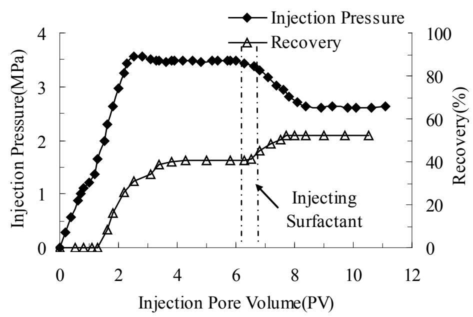
(a) With interfacial tension of 0.0593mN/m



(b) With interfacial tension of 0.0092mN/m



(c) With interfacial tension of 0.00071mN/m



(d) With interfacial tension of 0.000049mN/m

Figure 5
Curves of Injection Pressure and Recovery with Injection Pore Volume at Different Interfacial Tensions

As can be seen from Figure 5(a-d), the injection pressure rose sharply during the first water flooding, and the peak was achieved when the volume of injecting water reached 2~2.5 PV, then the pressure became gradually stable after showing a small drop. The injection pressure dropped slowly and then gradually tended to balance after injecting surfactant slug. In short, surfactant formulations with different ultra-low interfacial tensions could have certain effect of reducing injection pressure. On the side, at the beginning of the first water flooding, there was no oil at the outlet of core. When injecting a certain amount of water, the pressure increased to certain value, then the oil started coming out of the outlet and the recovery rose rapidly. The recovery changed unobvious after injecting 3 pore volume of the formation water. After injecting surfactant slug, the recovery rose in some extent and then stayed steady.

Analyzing its reason, the main characteristics of ultra-low permeability cores are small reservoir pore, fine throat, and high seepage resistance. During the process of the first water flooding, dispersed oil drops remain in reservoir pores and cannot flow through minute pores. The oil phase does not flow in a continuous state but in the state of small slug or dispersed drops. When oil drops or water drops flow through narrow throats, the injection pressure would increase because of Jamin Effect. The formation energy spreads slowly in low permeability reservoirs. These can cause low water intake capacity, high injection pressure, and low recovery efficiency. Surfactant can reduce interfacial tension and capillary resistance, make oil bead deform easily, and decrease the power on which oil droplets emit through the pore throat depending. It is easier for oil drop to change the shape of itself and flow through the throat. So surfactant can reduce injection pressure and enhance oil recovery of ultra-low permeability cores.

Figure 6 shows the two relation curves, including the curve between the decompression rate and interfacial tension, and another is the recovery and interfacial tension. The decompression rate is equal to the difference between stable pressure of the first water flooding and that of the second water flooding divided by that of the first water flooding.

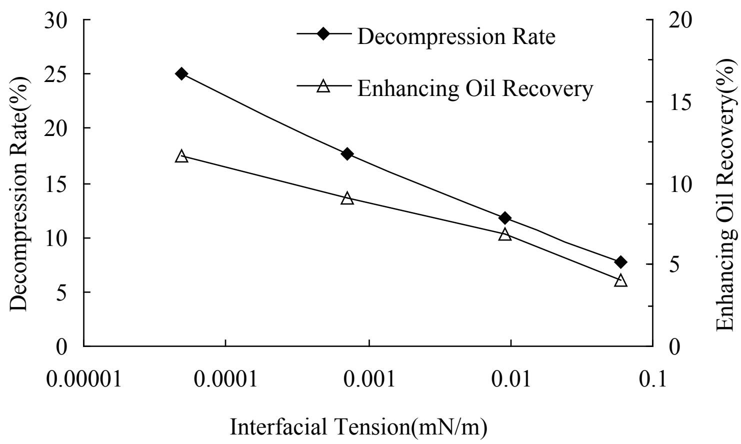


Figure 6
Impacts of Interfacial Tension on Decompression Rate and Enhancing Oil Recovery

As can be seen from Figure 6, when interfacial tension was 5.93×10^{-2} mN/m, decompression rate reached 7.65%, and recovery was improved by 4.09%. And when ultra-interfacial tension was 4.9×10^{-5} mN/m, decompression rate reached 25%, and recovery was improved by 11.6%. The effect of reducing injection pressure gradually strengthened and the extent of enhancing oil recovery gradually increased with the decreasing of interfacial tensions. Analyzing its reason, the lower interfacial tension is, the easier the deformation of residual oil is, the smaller the resistance caused by Jamin effect when oil beads travel through small throat. Thus, more and more residual oil is gradually emulsified and produced with lower interfacial tension. Meanwhile, owing to the reduction of residual oil, the flowing space of water phase increases gradually, so sweep efficiency is becoming larger, the relative permeability of water phase becomes higher, and injection pressure drops even further. In all, for ultra-low permeability core, the lower interfacial tension is, the better the effect of reducing injection pressure is, and the higher the extent of enhancing oil recovery is.

CONCLUSIONS

For the selected ultra-low permeability core whose gas log permeability was 0.52×10^{-3} μm^2, the vast majority of throats of core varied in width from 2.5 μm to 15 μm.

The injection pressure of the core rose sharply during the first water flooding,then the pressure became gradually stable after the volume of injecting water reached 2~2.5 PV. The pressure is higher about 3.5 MPa. There was no more oil at the outlet of the core after 3 PV. The recovery is lower about 40%.

The surfactant formulations with different ultra-low interfacial tensions could have certain effect of reducing injection pressure and enhancing oil recovery. And the lower interfacial tension is, the easier the deformation of residual oil is, the better the effect of reducing injection pressure is, the higher the extent of enhancing oil recovery is. When interfacial tension was 4.9×10^{-5} mN/m, decompression rate reached 25%, and recovery was improved by 11.6%.

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Error Rates of Older and Younger Groups

Number	Group 1	Group 2	Total	Older 1	Younger 1
1	A11	A21	A31	A51	Y1
2	A12	A22	A32	A52	Y2
3	...	...	...	...	...
...	...	...	...	...	...
n	A1n	A2n	A3n	A5n	Yn

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