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GAME THEORY AND 2 x 2 STRATEGIC GAMES APPLIED FOR MODELING OIL AND GAS INDUSTRY DECISION-MAKING PROBLEMS

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ABSTRACT. Oil and gas resources have been considered valuable assets, associated with potential conflicts due to distinct interests of many agents involved in their exploration, such as producing and consuming countries, governments and companies. These conflicts can show up under many situations and market conditions, such as partnerships, joint development, optimal outputs and reserve maximization. Game theory is known as a methodology that improves the decision-making processes by better understanding the players' specific motivations, strategic interactions and payoff estimation. A widely used framework for modeling social and economic phenomena is the 2 x 2 strategic games, of which include classical forms such as Prisoner's Dilemma, Stag Hunt, and Battle of Sexes. Therefore, this paper proposes to examine relevant realistic and real-world cases of the oil and gas industry in the form of 2 x 2 strategic games, aiming to investigate game theory approaches to aid in the discussion and resolution of the main dilemmas faced.

Keywords: Game theory, 2 x 2 strategic games, oil and gas.

Potential game theory applications in the oil & gas industry:

- ➔ Competitive bidding (tenders)
- ➔ Negotiations between partners
  - ◆ Key trade offs
- ➔ Joint ventures & partnerships
- ➔ Rivalry between service providers
- ➔ Employee union relationships
- ➔ Division of oil & gas earnings in Russia
- ➔ Conflicts among countries concerning oil & gas pipelines
  - ◆ In the Caucasus region
- ➔ Regional rivalries in Iraq about the division of oil & gas resources and revenues


KIEV
UKRAINE
MOL.
CHISINAU
ROM.
BUL.
Dniester
Dnieper
Siverskyi Donets
Don
Volga
Ural
KAZAKHSTAN
Aral Sea
SEA OF AZOV
Crimea
RUSSIA
UZBEKISTAN
BLACK SEA
CASPIAN SEA
Danube
Prut
Bosporus
SEA OF MARMARA
GEORGIA
TBILISI
ARMENIA
Lake Sevan
YEREVAN
AZERBAIJAN
BAKU
TURKMENISTAN
Garabogazköl Aylagy
ANKARA
TURKEY
Lake Tuz
Lake Egirdir
Lake Beysehir
Euphrates
Tigris
Lake Van
Lake Urmia
IRAN
TEHRAN
SYRIA
IRAQ
CYPRUS
0 100 km
0 100 mi


Caucasus
RUSSIA
KAZAKHSTAN
Caspian Sea
North Caucasus
Abkhazia
Sukhumi
Black Sea
South Ossetia
Kutaisi
Tskhinvali
GEORGIA
Tbilisi
Batumi
TURKEY
ARMENIA
AZERBAIJAN
Baku
Nagorno-Karabakh
Yerevan
Stepanakert
Nakhchivan (Azer.)
Nakhchivan City
IRAN
200 Kilometers
200 Miles
N

A 2×2 game can be fully described by only 8 numbers (the payoffs of the two players). This simplicity gives them power (Robinson & Goforth, 2005).

- ➔ Topology results from the preferences of the players.
- ➔ The examination of different kinds of games renders what may be called topography.

Player preferences provide a useful framework for relating games.

Robinson, D., & Goforth D. (2005). *The topology of the 2×2 games: A new periodic table*. London and New York: Routledge, Taylor and Francis Group.

Robinson & Goforth (2005) *“rule out indifference”* (page 5), thereby excluding games in which at least two of the payoffs of one player are tied, such that that player is indifferent between the two corresponding strategies.

➔ As a result, classic games such as the coordination games (including pure coordination, coordination with assurance, and the battle of the sexes) are not considered.

Robinson & Goforth (2005) also consider games that can be converted to one another via a monotonic transformation, to be equivalent.

➔ As a result of these two simplifications, the 8 payoff numbers combine to form a group of 144 games that may be characterized as truly unique.

Robinson & Goforth (2005) assigned payoffs using the numbers 1, 2, 3 and 4.

The payoff space is the discrete space $\{1, 2, 3, 4\} \times \{1, 2, 3, 4\}$.

Number of 2×2 games with payoffs ranging from 1 to 4, with payoffs allowed to be equal:

$$(\text{games for player 1}) \times (\text{games for player 2})$$
$$= (4\times4\times4\times4)\times(4\times4\times4\times4) = 4^4\times4^4 = 4^8 = 65{,}536$$

Considering row and column swaps, only 25% of these games are distinct:

$$65{,}536 \div 4 = 16{,}384$$

Number of 2×2 games with no payoffs allowed to be equal:

$$(\text{games for player 1})\times(\text{games for player 2})$$
$$= (4\times3\times2\times1)\times(4\times3\times2\times1) = 4!\times4! = 24\times24 = 576$$

These games account for the following percentage of the total population:

$$576\div65{,}536\times100 = 0.88\%$$

Number of 2×2 games, with two payoffs allowed to be equal:

$$(\text{games for player 1})\times(\text{games for player 2})$$
$$= (4\times4\times3\times2)\times(4\times4\times3\times2) = 96\times96 = 24\times24 = 9{,}216$$

These games represent the following percentage of the total population:

$$9{,}216\div65{,}536\times100 = 14.1\%$$

Number of 2×2 games games with three payoffs allowed to be equal:

(games for player 1)×(games for player 2)
= (4×4×4×3)×(4×4×4×3) = 192×192 = 24×24 = 36,864

These games represent the following percentage of the total population:

36,864÷65,536×100 = 56.3%

Number of two-by-two games with all four payoffs being equal:

(games with all 4 payoffs equal, for player 1)×(games with all 4 payoffs equal, for player 1)+[(games with all 4 payoffs equal, for player 1)×(all games excluding games with all 4 payoffs equal, for player 2)] + [(all games excluding games with all 4 payoffs equal, for player 1)×(games with all 4 payoffs equal, for player 2)]

$$= (4\times4)+[(4)\times(4\times4\times4\times4-4)]+[(4\times4\times4\times4-4)\times(4)]$$

$$= 16+4^5+4^5 = 1008+1008 = 2032$$

These games represent the following percentage of the total population:

$$2,016 \div 65,536 \times 100 = 3.1\%$$

Python program

	Number	%
Games with payoffs between 1 and 4	65,536	100.00
Constant/zero sum games	452	0.69
Symmetric games	256	0.39
Games with zero (0) tied payoffs	576	0.88
Games with at least one (1) payoff tie	64,960	99.12
Games with all four (4) payoffs tied	2,032	3.1
Games with zero (0) strict Nash equilibria	31,264	47.71
Games with one (1) strict Nash equilibrium	31,680	48.34
Games with two (2) strict Nash equilibria	2,592	3.96
Games with no dominant strategy	33,856	51.66
Games with dominant strategy for one player	26,496	40.43
Games with dominant strategies for both players	5,184	7.91

According to Robinson & Goforth (2005), the following are the most relevant 2×2 games among the 144:

- ➔ Coordination games
- ➔ Battle of Sexes
- ➔ Stag Hunt
- ➔ Chicken
- ➔ Prisoner’s Dilemma

Coordination Game

Opponent

		A	B
You	A	1, 1	0, 0
	B	0, 0	1, 1

Column Player

Row Player		Left	Right
	Top	(10,10)	(0,0)
	Bottom	(0,0)	(1,1)

(T,L) *Pareto Dominates* (Bottom Right). It is reasonable to conclude that the players will end up playing (T,L).

Coordination Games

		Buyer	
		new	old
Supplier	new	20,20	0,0
	old	0,0	5,5

- This game has two Nash equilibria (new,new) and (old,old)
- Real-life examples: Beta vs VHS, Mac vs Windows vs Linux, others?

- Each player wants to do what the other does
  - which may be different than what they *say* they'll do
- How to choose a strategy? Nothing is dominated.

		WOMAN	
		Boxing	Shopping
MAN	Boxing	2 , 1	0 , 0
	Shopping	0 , 0	1 , 2

Battle of the Sexes

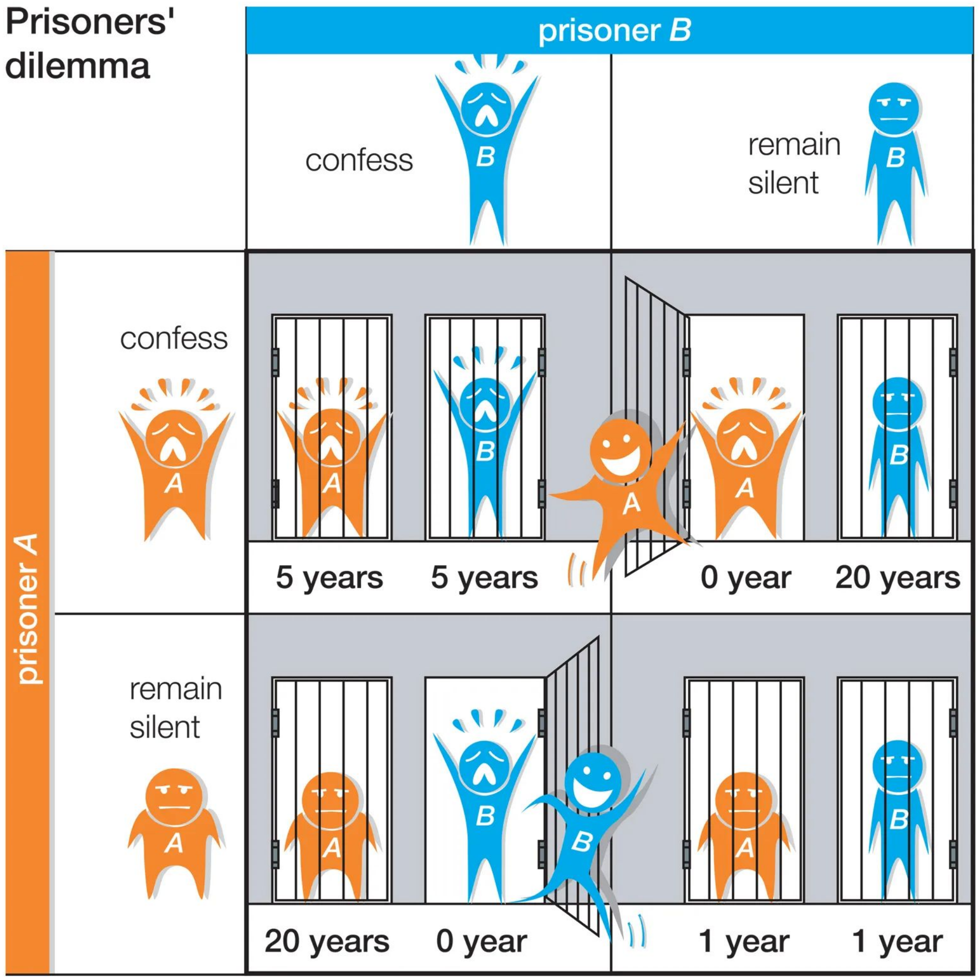
	LW	WL
LW	2,1	0,0
WL	0,0	1,2

- Both pure strategies are Nash Equilibria
- Are there any other Nash Equilibria?
- There is at least another mixed-strategy equilibrium (usually very tricky to compute, but can be done with simple examples)

The Stag Hunt Game

Stag: Cooperation • **Hare**: Defect

		HUNTER 1	
		STAG	**HARE**
HUNTER 2	**STAG**	**5, 5**	**0, 2**
	HARE	**2, 0**	**1, 1**



Prisoners' dilemma
prisoner B
confess
remain silent
prisoner A
confess
remain silent
5 years
5 years
0 year
20 years
20 years
0 year
1 year
1 year

THE PRISONER'S DILEMMA

	B stays silent (cooperates)	B betrays A (defects)
A stays silent (cooperates)	Both serve 1 year	A serves 3 years, B goes free
A betrays B (defects)	A goes free, B serves 3 years	Both serve 2 years

SOURCE: Wikipedia

According to Willigers et al. (2009) and Bratvold & Koch (2011), the oil producers' dilemma is an example of the Prisoner's Dilemma practical application in the oil and gas industry. This game consists of two generic oil-producing countries (A and B) with the same goal of maximizing their oil revenues by deciding how much oil to produce as their strategies. For this practical application, it was assumed that each of the two countries could choose from two options: (i) low production (10 barrels of oil); and (ii) high production (20 barrels of oil). Each player decides to adopt the strategy that they believe will maximize their own oil revenues. The game assumes cardinal information using the oil price as a function of the total oil produced by the two countries (A and B), where there is a clear inverse relationship between oil output production and its price (Willigers et al., 2009). Table 2 synthesizes the payoffs for both countries.

Table 2 – Oil producers' dilemma.

Source: Willigers et al. (2009) and Bratvold & Koch (2011).

Country A	Country B	
	Low Production	High Production
Low Production	\$1400; \$1400	\$750; \$1500
High Production	\$1500; \$750	\$800; \$800

of low production generated higher payoffs. The main issue faced in this game is that there is an incentive for both agents to break the deal and behave as a free-riding player, aiming to achieve the highest payoff as possible. Consequently, it is unlikely to expect that both countries will always limit their production to a low-level range without an additional contractual or enforcement process (Bratvold & Koch, 2011). This break off will occur if one player considers the incentives for deviating, which includes their expected gain being higher than the coordinated solution (Kelly, 2003).

Schitka (2014) proposed a realistic non-cooperative game for the joint development or unitization of a reservoir involving neighboring landowners, simulating a practical application according to the regulations of US and Canada. This game follows the logical structure of the Prisoner's Dilemma, where two landowners have oil and gas resources in their bordering properties. Both landowners can choose between two different strategies: (i) joint development, cooperation or unitization in order to develop together these oil and gas resources; and (ii) drill solo, each landowner chooses to develop these resources by themself aiming to extract more, and faster, than their neighbor. Schitka (2014) mentioned that a unitization strategy could potentially allow a more efficient exploration of the reservoir and more oil and gas to be extracted. However, each landowner also has the opportunity to drill as many wells as possible, being able to extract more, and faster, oil and gas from these wells. Table 3 summarizes the payoffs identified for this hypothetical game.

Table 3 – Reservoir joint development or unitization negotiations.

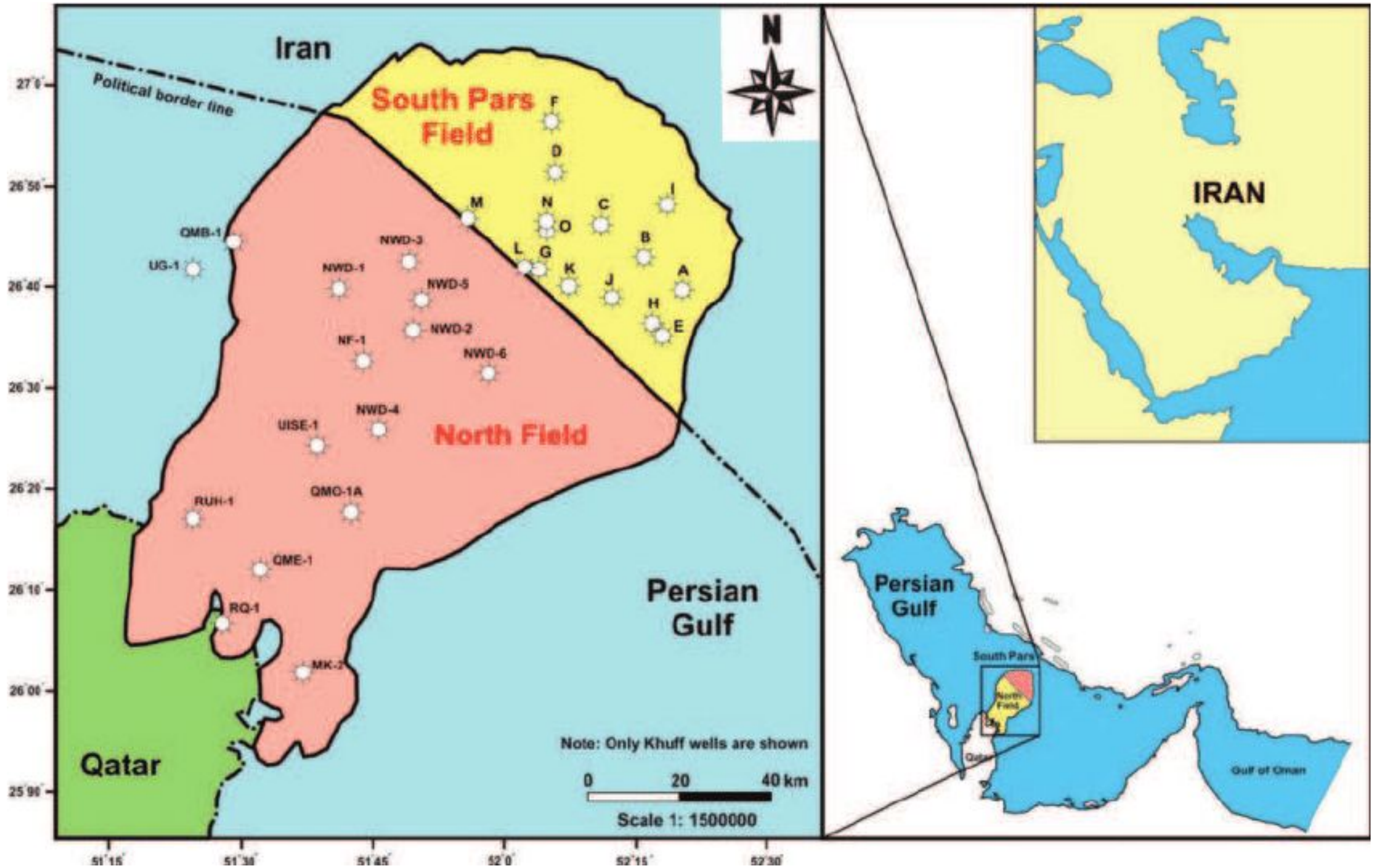
Source: Schitka (2014).

Player 1	Player 2	
	Joint development	Drill solo
Joint development	125; 125	50; 150
Drill solo	150; 50	100; 100

In this non-cooperative game, the only Nash equilibrium and Maxi-min solution is identified as both players assuming the strategy of drilling solo. However, each player has a strong tendency to explore their common oil and gas resources based on the chance of obtaining more oil and gas than their neighbor. It is possible to observe that the highest payoffs are in the option of drilling solo, by assuming a free-riding strategy. Nevertheless, this choice results in an inefficient development of the reservoir as a whole because of quick pressure depletion and gas cap releasing, which characterizes the drop of reservoir's driving force that allows the resources to be extracted (Schitka, 2014).

Finally, Esmaeili et al. (2015) used the same logical structure of the Prisoner's Dilemma, but here with ordinal information, to understand and model the conflict between Iran and Qatar in the development of two common oil fields (South Pars and North Dome) located within their borders. This game assumed that Iran and Qatar have two possible strategies: (i) low extraction rate (LER); and (ii) high extraction rate (HER). At first, both countries may presume that the more they extract, the more they gain. On the other hand, the oil reserves would quickly drop and the extracting costs would increase if the high extraction strategy was applied by both countries. However, if both countries chose the strategy of a low extraction rate (LER), the reservoirs' levels would slowly decrease, and the countries would enjoy long-term profits. In other words, it seems that a cooperative strategy is indicated for both countries. Nevertheless, there is still an incentive to perform a free-riding strategy by choosing a high extraction rate (HER) as long as the other player prefers a low extraction rate (LER) option, in order to achieve the highest possible payoff, which can be visualized in Table 4.


IRAN
Persian Gulf
KUWAIT
South Pars
BAHRAIN
North Field
QATAR
Gulf of Oman
UNITED ARAB EMIRATES

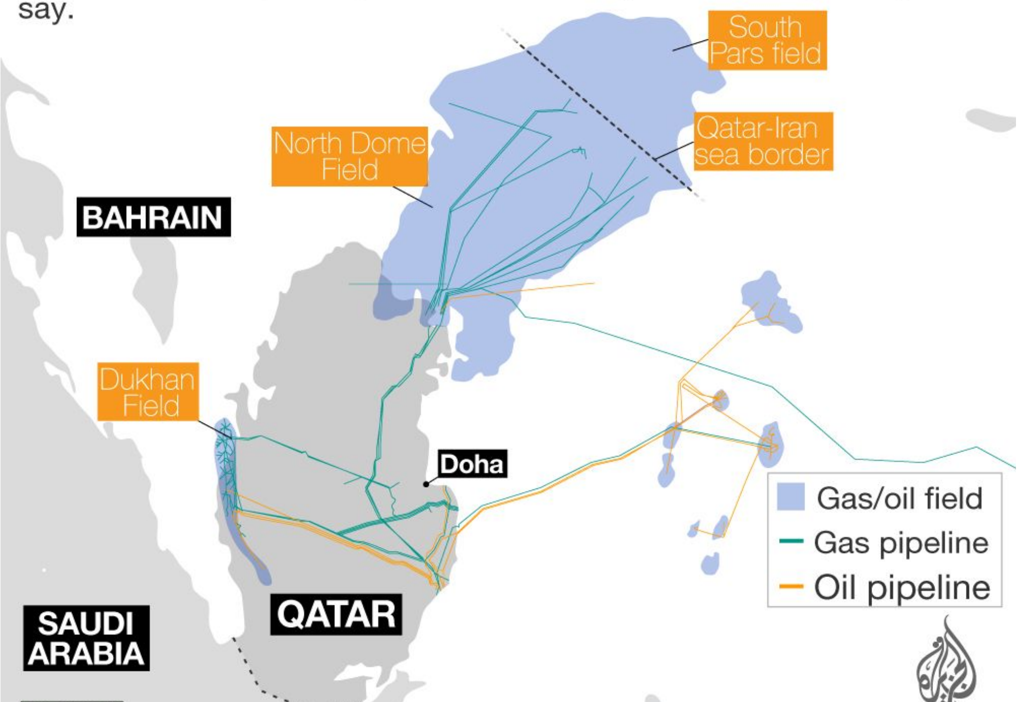


Iran
Political border line
South Pars Field
North Field
Persian Gulf
Qatar
N
F
D
M
N
O
C
I
B
L
G
K
J
A
H
E
QMB-1
UG-1
NWD-3
NWD-1
NWD-5
NWD-2
NF-1
NWD-6
NWD-4
UISE-1
QMC-1A
RUH-1
QME-1
RQ-1
MK-2
Note: Only Khuff wells are shown
0 20 40 km
Scale 1: 1500000
27'0'
26'50'
26'40'
26'30'
26'20'
26'10'
26'00'
25'90'
51'15'
51'30'
51'45'
52'0'
52'15'
52'30'
IRAN
Persian Gulf
South Pars
North Field
Gulf of Oman

Qatar's major gas and oil fields

Qatar is the world's largest seller of liquefied natural gas (LNG). Most of the LNG comes from two major gas and oil fields, one of which is shared with Iran.

While the Gulf's diplomatic crisis is unlikely to affect energy prices in the short term, a prolonged rift could send prices soaring, analysts say.



Source: Al Jazeera, AFP, OPEC

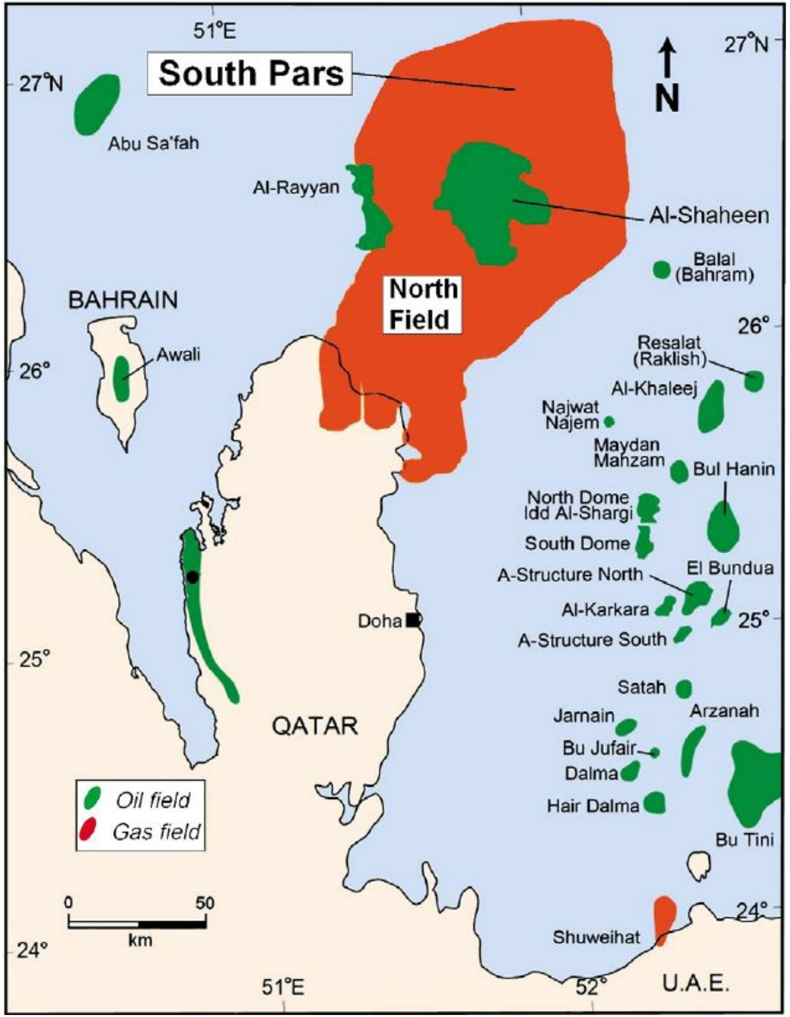

51°E
27°N
South Pars
N
Abu Sa'fah
Al-Rayyan
Al-Shaheen
Balal
(Bahram)
BAHRAIN
North
Field
26°
Resalat
(Raklish)
Awali
26°
Al-Khaleej
Najwat
Najem
Maydan
Mahzam
Bul Hanin
North Dome
Idd Al-Shargi
South Dome
El Bundua
A-Structure North
Al-Karkara
Doha
25°
A-Structure South
25°
Satah
Arzanah
Jarnain
QATAR
Bu Jufair
Dalma
Oil field
Gas field
Hair Dalma
Bu Tini
0
50
km
24°
Shuweihat
24°
51°E
52°
U.A.E.

Table 4 – Iran-Qatar conflict over the fields of South Pars and North Dome.

Source: Esmaeili et al. (2015).

Iran	Qatar	
	Low Extraction Rate (LER)	High Extraction Rate (HER)
Low Extraction Rate (LER)	2 ; 2	0 ; 3
High Extraction Rate (HER)	3 ; 0	1 ; 1

In this particular real-world application, Qatar enjoys the benefits of a higher extraction rate (HER) in a free-riding strategy. In contrast, Iran is making the least profit from these common oil and gas resources in the current situation by adopting the strategy of low extraction rate (LER) (Esmaeili et al., 2015). Nonetheless, the current situation can change as soon as Iran implements a different strategy in order to achieve a higher extraction rate. In any Prisoner's

Esmaeili et al. (2015) proposed a game based on a real-world conflict between Iran and Iraq for the exploration and production of their shared oil and gas resources, which includes 20 common oil and gas fields located along their border. Both countries have two possible strategies: (i) maximum extraction rate (MER), the highest oil and gas production rate in the shortest time; and (ii) low extraction rate (LER), the lowest oil and gas production rate according to the reservoir conditions. The logical structure behind the exploration of these shared resources is that if both countries cooperate and explore these fields with a reasonable extraction rate, less than the maximum rate, the long-term benefits of proper maintenance will exceed the revenue losses from extracting less than the maximum (Esmaeili et al., 2015). Fiani (2015) argued that the best outcome for both players in a classical Stag Hunt game strongly depends on their commitment to their initial agreement (Table 5).


MAJOR OIL FIELDS OF THE ARABIAN-IRANIAN BASIN REGION
0 100 200 300 mi
0 200 400 km
TURKEY
TURKMENISTAN
Caspian Sea
SYRIA
Karkuk
IRAQ
IRAN
JORDAN
Ahvāz
Marūn
Majnūn
Āghā Jārī
Al-Rumaylah North
Al-Rumaylah
Gach Sārān
Al-Rawḍatayn
KUWAIT
ARABIAN–IRANIAN BASIN
ZAGROS FOLD BELT
Persian Gulf
Al-Burqān
Al-Zuluf
Saffāniyyah
Manīfah
Al-Barrī
Al-Qaṭīf
Abqaiq
Abu Saʾfah
QATAR
Umm Al-Shaʾif
Khurayṣ
Al-Zukum
Gulf of Oman
Al-Ghawār
UNITED ARAB EMIRATES
Bū Ḥaṣā
Al-Shabah
SAUDI ARABIA
OMAN
Red Sea
ERITREA
YEMEN
Arabian Sea
ETHIOPIA
DJIBOUTI
Gulf of Aden
Supergiant oil fields

Table 5 – Iran-Iraq conflict over shared oil and gas resources located in their borders.

Source: Esmaeili et al. (2015).

Iran	Iraq	
	Low Extraction Rate (LER)	Maximum Extraction Rate (MER)
Low Extraction Rate (LER)	3 ; 3	0 ; 2
Maximum Extraction Rate (MER)	2 ; 0	1 ; 1

The highest outcome for both countries is a Nash equilibrium that comprehends the strategy of a low extraction rate (LER). There is also another Nash equilibrium when both players choose a maximum extraction rate (MER). In a classical Stag Hunt game, the players' choices are deeply affected by mutual trust and past negotiations, which can be tough due to a history of wars, conflicts and invasions between Iran and Iraq (Esmaeili et al., 2015). The current situation states that the oil extraction rate of Iraq is more than double than the rate of Iran. It means that Iraq assumed a free-riding strategy and achieved better outcomes than Iran in this situation. However, it is expected that in the near future both countries reach an agreement to develop their common oil and gas resources, which should result in long-term benefits for both (Esmaeili et al., 2015).

Inaba (2015; 2016) proposed a realistic application of a Stag Hunt game based on historical examples of business cooperation in Japanese oil and petrochemical plants, especially in the matters of energy-saving, actions on environmental problems, security of global competitiveness, and restructuring of production systems. This game is composed of two oil and petrochemical companies (A and B) that are evaluating the possibilities of cooperating and executing joint operations. Hence, both companies can assume two possible strategies: (i) continue with their independent business; and (ii) perform business cooperation. The main goal of this game is to evaluate the payoffs for both companies by choosing collaborative cooperation or by keep undertaking independent business, following the logical structure of a classical Stag Hunt game. Table 6 shows the players' payoffs for this practical application.

Table 6 – Cooperation dilemma faced by Japanese oil and petrochemical plants.

Source: Inaba (2015; 2016).

Company A	Company B	
	Independent business	Business cooperation
Independent business	1,-1 3 ; 2	3 ; 0 3,-3
Business cooperation	-2,2 0 ; 2	7 ; 4 3,-3

How to work out payoffs if relative gains are of concern

The Chicken game approach comes from an old James Dean movie, called "Rebel without a cause", where two teenage boys drive cars at high-speed toward a cliff edge to see who is the first one to brake and chicken out (Binmore, 2007). Fiani (2015) defines this classical game as a dangerous form of destructive competition, where two teenagers drive at high-speed towards each other to see who will deviate first. In a Chicken game, the coordinated solutions are usually the ones with the least-favored outcomes, where both players have high incentives to assume a different strategy from the other player in a free-riding strategy (Decanio & Fremstad, 2013).

Esmaeili et al. (2015) proposed a practical application of the Chicken game to analyze the conflict between Iran and Iraq in a region close to the Fakka oil field. This particular region has several historical border controversy issues. In 2009, an incident occurred when Iranian troops invaded this region for some period, and later left the territory due to a possible military reaction from Iraq. Therefore, in this situation, Iran and Iraq can assume two strategies: (i) (C), abandoning the region and not exploring the oil and gas resources; and (ii) (D), staying in the region and benefiting from the oil and exploration. Table 7 shows the payoffs for each player in this real-world situation.

SOURCES: CIA, International Petroleum Encyclopedia; ESRI

AP


50 miles
50 km
TURKEY
AFGHAN.
Area of detail
EGYPT
SAUDI ARABIA
SUDAN
Arabian Sea
Tigris River
IRAN
Tigris R.
Al-Fakkah oil field
Euphrates R.
IRAQ
KUWAIT
Persian Gulf

Table 7 – Iran-Iraq conflict over the Fakka oil field region.

Source: Esmaeili et al. (2015).

Iran	Iraq	
	(C)	(D)
(C)	3 ; 3	2 ; 4
(D)	4 ; 2	1 ; 1

The payoff outcomes indicated two Nash equilibria when players assume different strategic options, such as (C, D) or (D, C), where one of the countries would explore and produce the oil field obtaining the greatest benefits, while the other player would leave the area empty-handed (Esmaeili et al., 2015). The other possible outcomes of this conflict happen when both players select the same strategy (C), resulting in both countries leaving the field unexploited for the future. If both countries chose (D), a catastrophic outcome would happen, which could lead to military action, being the lowest payoff for both countries considering the high political risks (Esmaeili et al., 2015).

Schitka (2014) proposed a realistic application of an oil and gas reservoir allocation based on a classical Battle of the Sexes game. Assuming that both players agreed to make a joint reservoir development or unitization arrangement, another issue would show up. This issue is characterized as the allocation formula, which will determine what portion of the produced oil and gas each landowner will receive. This allocation formula can create several potential conflicts during the reservoir unitization negotiations to determine how the resources will be explored, and how the earnings will be distributed to the landowners. The main assumption of this game is that both players are in a more advantageous position by agreeing on an appropriated allocation formula, than when each one pursues their individual interests (Schitka, 2014), as demonstrated by the players payoffs in Table 8.

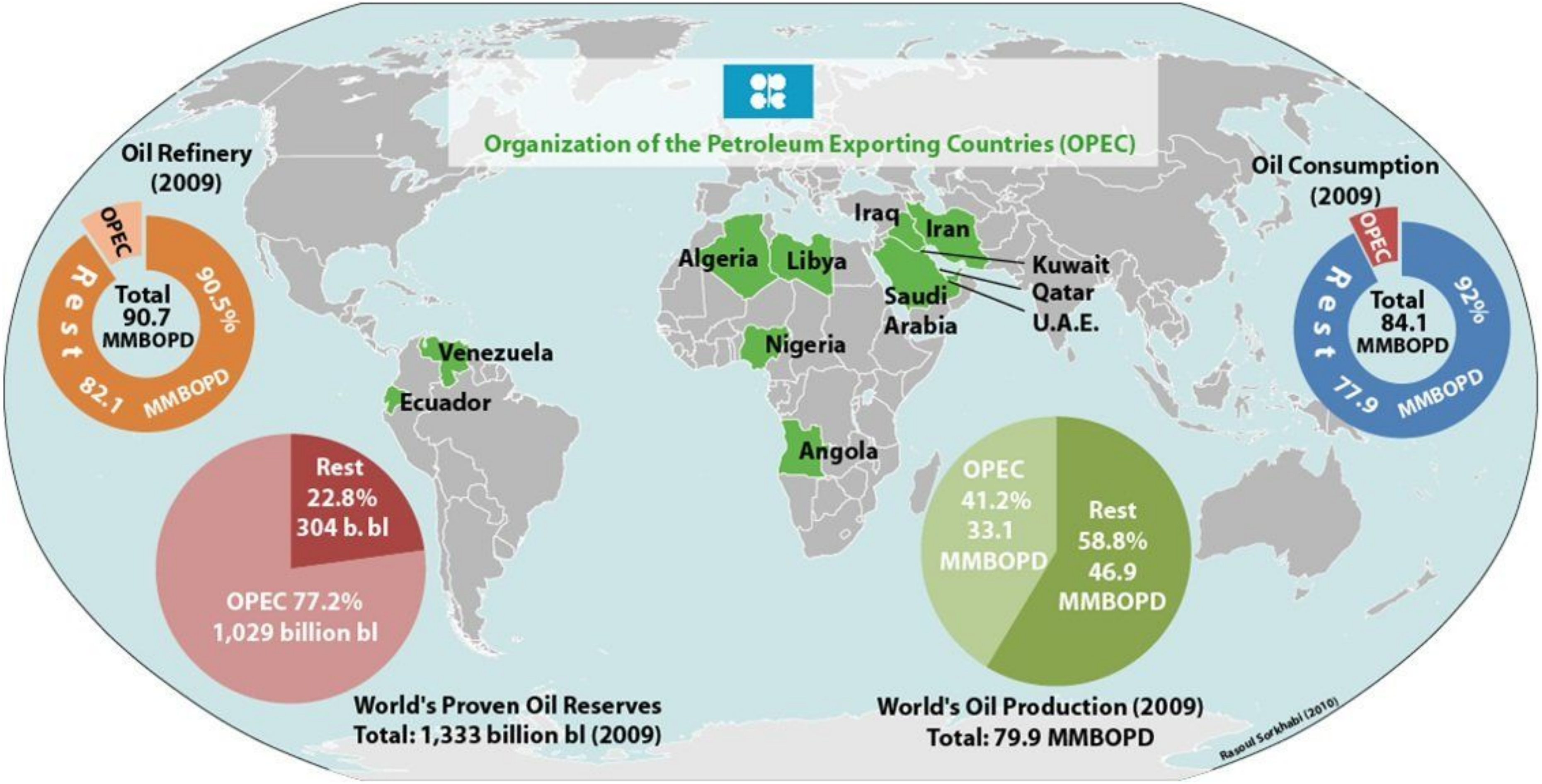
Table 8 – Allocation formula during joint development or unitization negotiations.

Source: Schitka (2014).

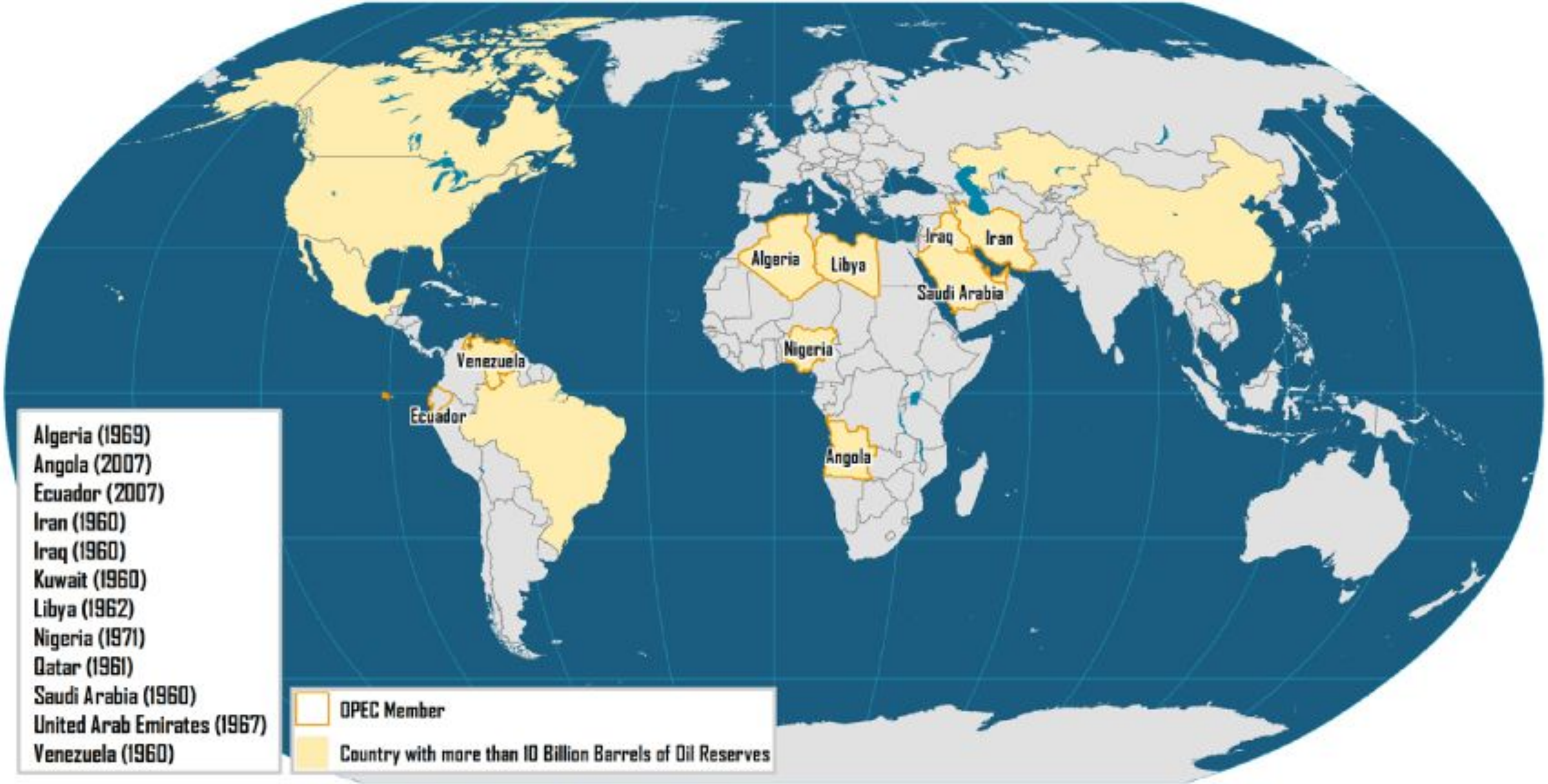
Player 1	Player 2	
	Unit Plan 1	Unit Plan 2
Unit Plan 1	50 ; 40	-100 ; -100
Unit Plan 2	-100 ; -100	40 ; 50

The payoff outcomes show that the strategy of "Unit Plan 1" is more desirable to player 1, while the strategy of "Unit Plan 2" is more appropriate to player 2. However, only the coordination of both players in the same strategy will prevent them from having negative payoffs. In other words, both coordinated strategies are identified as Nash equilibria, indicating a more efficient development of the common reservoirs, allowing more oil and gas to be extracted than otherwise would have been possible by each player by themself. Schitka (2014) mentioned that unitiza-

Wood et al. (2016) proposed to evaluate the world oil market during the 1960s and 1970s based on an adaptation of the classical Battle of the Sexes game by analyzing two players, namely: (i) the OPEC countries; and (ii) the Seven Sisters. The OPEC countries are characterized as a set of countries with abundant oil reserves joined together in an association to defend their specific interests. On the other side, the Seven Sisters represented seven major oil firms, namely Shell, BP, Gulf, Chevron, Texaco, Exxon and Mobil, with significant dominant force in global petroleum markets, especially in the decades following World War II (Wood et al., 2016). During the 1960s and 1970s, about three-quarters of the proven oil and gas reserves in the world were located in OPEC countries (Mommer, 1999). Significant changes in the oil and gas industry were identified during this period (1960s and 1970s), where OPEC countries and major oil companies were fighting to get overall market control and not caring so much about price or revenue (Johnston, 2008).



Organization of the Petroleum Exporting Countries (OPEC)
Oil Refinery (2009)
OPEC
Rest
Total 90.7 MMBOPD
90.5%
82.1 MMBOPD
Oil Consumption (2009)
OPEC
Rest
Total 84.1 MMBOPD
92%
77.9 MMBOPD
Iraq
Iran
Algeria
Libya
Kuwait
Qatar
U.A.E.
Saudi Arabia
Nigeria
Venezuela
Ecuador
Angola
Rest 22.8% 304 b. bl
OPEC 77.2% 1,029 billion bl
OPEC 41.2% 33.1 MMBOPD
Rest 58.8% 46.9 MMBOPD
World's Proven Oil Reserves
Total: 1,333 billion bl (2009)
World's Oil Production (2009)
Total: 79.9 MMBOPD
Rasoul Sorkhabi (2010)


Algeria
Libya
Iraq
Iran
Saudi Arabia
Nigeria
Venezuela
Ecuador
Angola
Algeria (1969)
Angola (2007)
Ecuador (2007)
Iran (1960)
Iraq (1960)
Kuwait (1960)
Libya (1962)
Nigeria (1971)
Qatar (1961)
Saudi Arabia (1960)
United Arab Emirates (1967)
Venezuela (1960)
OPEC Member
Country with more than 10 Billion Barrels of Oil Reserves

According to Wood et al. (2016), the OPEC countries and the Seven Sisters were a heterogeneous population of agents struggling for control over the global petroleum market. The proposed game assumed that the OPEC countries could have two strategies: (i) full production (active rule), supplying the world with abundant oil at low prices; and (ii) prorate (passive rule), cutting the oil production to a specific fraction of the available output. On the other hand, the Seven Sisters strategies were identified as the following: (i) dominate (active rule), struggling to set oil prices and production levels; and (ii) acquiesce (passive rule), letting the OPEC countries control the prices and the production levels while focusing on other aspects of the oil industry, such as logistics and end-use sales. Table 9 shows the payoffs associated with the possible strategies of both players.

Table 9 – Market dominance of OPEC countries and Seven Sisters in the 1960s and 1970s.
Source: Wood et al. (2016).

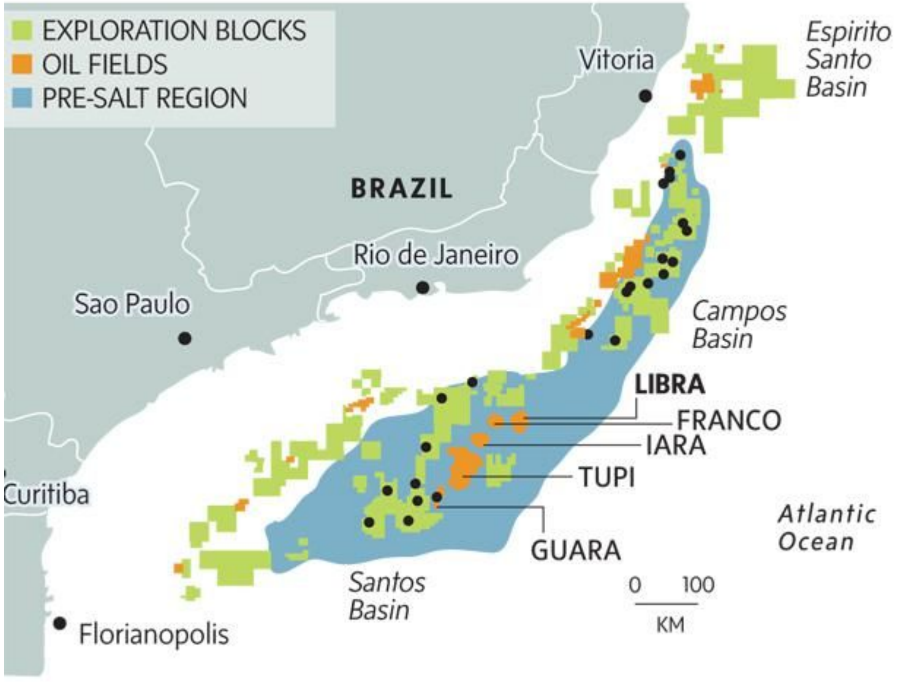
OPEC Countries	Seven Sisters	
	Dominate	Acquiesce
Full production	A ; B	C ; D
Prorate	D ; C	B ; A

Wood et al. (2016) assumed that the payoffs followed the sequential logic of "B" > "A" > "C" > "D". The Nash equilibria would only be achieved when both players agreed to coordinate and choose the same strategy. It is possible to observe that "B" was the payoff earned by the agent who controlled the market, while "A" was the payoff for coordinating with a dominant opponent. These payoff outcomes indicated that this was a leader-follower model, which offered the greatest payoffs for both players when they cooperated, and the leader earned a slightly higher payoff than the follower. The payoffs "C" and "D" were associated with coordination failures with the lowest possible gains for both players. The logical structure of this practical application is very similar

Coordination games:

- ➔ Cooperation among oil & gas companies in unitization processes in Brazil
- ➔ Petrobras (the Brazilian Oil Company) was predominant in the country's oil & gas market
  - ◆ Leading player with strong interests in negotiations

BRAZILIAN OIL FIELDS



CARRIE COCKBURN/THE GLOBE AND MAIL » SOURCES: PETROBRAS; WOOD MACKENZIE; GRAPHICS NEWS

WHERE THE OIL IS

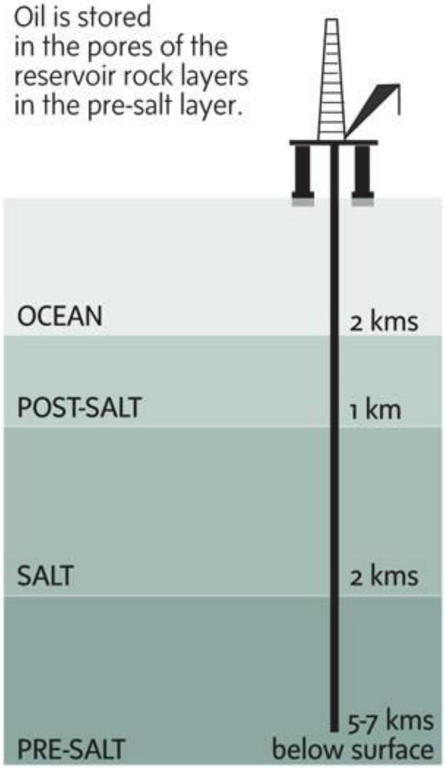


Table 10 – Practical application of unitization agreements in Brazil.
Source: Amorelli & Carpio (2016).

Company 1	Company 2	
	Cooperate (C)	Not cooperate (NC)
Cooperate (C)	π_{C1} ; π_{C2}	π'_{C1} ; π_{NC2}
Not cooperate (NC)	π_{NC1} ; π'_{C2}	π_{p1} ; π_{p2}

Results of the the leading player deciding to hold a non-cooperative strategy (assuming the others would cooperate):

- ➔ Crisis of confidence for future negotiations resulted
- ➔ Lack of willingness of other companies to invest in Brazil
  - ◆ Bargain for better conditions
  - ◆ Sell their rights and leave the region

Fattouh et al. (2016) used a framework based on a Coordination game to analyze the Saudi Arabian strategic choices in order to achieve its objectives of maintaining market share and maximizing revenue. There is a huge trade-off identified between these two objectives, depending on market conditions and the behavior of other major oil producers. In other words, the strategic choices of other OPEC countries could strongly impact in Saudi Arabia's specific objectives of market share and revenue. Therefore, the players involved are: (i) Saudi Arabia; and (ii) other OPEC countries. The game is structured by assuming two strategies: (i) cutting oil output; and (ii) does not change oil output. Fattouh et al. (2016) mentioned that the advent of US shale reservoirs changed the market conditions, making it more difficult for Saudi Arabia and other OPEC countries to choose their oil output strategy. These market conditions were evaluated in

Table 11 – Saudi Arabia and OPEC countries in an elastic US supply.
Source: Fattouh et al. (2016).

Elastic US Supply (Game 1)		
Saudi Arabia	Other OPEC Countries	
	Cut output	Does not change output
Cut output	–C ; –C	–A ; O
Does not change output	O ; –A	O ; O

Table 12 – Saudi Arabia and OPEC countries in an inelastic US supply.
Source: Fattouh et al. (2016).

Inelastic US Supply (Game 2)		
Saudi Arabia	Other OPEC Countries	
	Cut output	Does not change output
Cut output	A ; A	C ; B
Does not change output	B ; C	O ; O

OPEC countries. The game is structured by assuming two strategies: (i) cutting oil output; and (ii) does not change oil output. Fattouh et al. (2016) mentioned that the advent of US shale reservoirs changed the market conditions, making it more difficult for Saudi Arabia and other OPEC countries to choose their oil output strategy. These market conditions were evaluated in

(Robinson & Goforth, 2005). The results of this game indicated that under the uncertainty of US shale elasticity, it is safer for Saudi Arabia to assume that the US shale oil supply is elastic and does not cut its oil output. However, after learning more about this new source of oil sup-

same strategy of cutting output (Robinson & Goforth, 2005). Fattouh et al. (2016) concluded that Saudi Arabia and other OPEC countries would have better benefits under the assumption of an inelastic US oil supply and that there is a single optimal coordinated option.