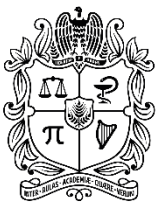

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A Framework to study Antifragility for Enterprise Risk Management: Case Study of Unconventional Oil and Gas Operations in Latin America

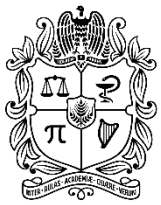
Óscar Bravo Mendoza

Universidad Nacional de Colombia

Departamento Ingeniería de Sistemas e Industrial

Bogotá, Colombia

2021



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Marco de Referencia para la aplicación de la Antifragilidad en la Gestión de Riesgos Empresarial: Estudio de Caso del Desarrollo de Operaciones de Yacimientos no Convencionales en Latinoamérica

Óscar Bravo Mendoza

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Departamento Ingeniería de Sistemas e Industrial

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A Framework to study Antifragility for Enterprise Risk Management: Case Study of Unconventional Oil and Gas Operations in Latin America

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In partial fulfillment of the requirements of the degree of
Doctor of Philosophy in Industry and Organizations

Thesis Supervisor: Diego Fernando Hernández Losada, Ph.D.

Research focus: Organizational Research; Risk Assessment and Risk Management

Universidad Nacional de Colombia
Departamento Ingeniería de Sistemas e Industrial
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2021

I want to express my gratitude to:

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Carmen Cecilia Mogollón and all the people who inspired me and gave me all the support and wisdom to make this dream come true.

My thesis supervisor Diego Fernando Hernández, Ph.D. Thank you for inviting me and allowing me to do my research.

Declaración de obra original

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Fecha 13/04/2021

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Abstract

A Framework to study Antifragility for Enterprise Risk Management: Case Study of Unconventional Oil and Gas Operations in Latin America

This research builds on the most recent organizational resilience theories to elaborate heuristic tests to prove the antifragility concept, the last defined step for companies to cope with VUCA (Volatile, Uncertain, Complex, and Ambiguous). Given its novelty, the body of knowledge regarding antifragility is weak. There are only a few definitions and attributes to describe antifragility at the organizational level and a total absence of real firm cases, theory, and hypotheses research. The antifragility concept offers new management and risk assessment tools to organizations eager to survive and take advantage of the new opportunities that unfold behind the threat of uncertainty.

Antifragility goes beyond business continuity and resilience by focusing on the firms' ability to deliver products and services at acceptable levels after a disruptive event and taking advantage of the upside risk involved in uncertainty to improve performance and foster innovation and growth. This study's main contribution is defining proper metrics to identify and rank the organizational resilience level after an extreme event and define a framework to describe the selected antifragile companies' common attributes and competencies.

The results from this study will serve as the basis for organizations that struggle to operate in VUCA and are exposed to surprising, extreme events, also known as Black Swans. Additionally, the proposed antifragility framework and measurement system will also strengthen the risk assessment and management disciplines.

Keywords: Resilience, Antifragility, Organizational Resilience, Optionality, Unconventionals, Risk-Performance Metrics.

Resumen

Marco de Referencia para la aplicación de la Antifragilidad en la Gestión de Riesgos Empresarial: Estudio de Caso del Desarrollo de Operaciones de Yacimientos no Convencionales en Latinoamérica

Esta investigación se basa en la literatura más reciente en materia de resiliencia organizacional, para probar de manera heurística el concepto de antifragilidad, el último paso definido para que las empresas puedan desempeñarse en ambientes VICA (Volatilidad, Incertidumbres, Complejidad y Ambigüedad). La antifragilidad es un concepto nuevo, para el cual el estado del arte es deficiente. Existen solamente algunas definiciones y atributos en la literatura que permiten describirla a nivel organizacional, y una total ausencia de casos de estudio de empresas, que permitan la generación de hipótesis y teorías de investigación. El concepto de antifragilidad ofrece nuevas herramientas para las organizaciones que requieren sobrevivir y poder aprovechar las oportunidades que subyacen los temores por la incertidumbre.

La antifragilidad va más allá de la continuidad del negocio y la resiliencia al enfocarse en la capacidad de las empresas para entregar productos y servicios con niveles aceptables de calidad luego de un evento disruptivo, aprovechando las posibilidades que brinda la incertidumbre para mejorar el desempeño e incrementar la innovación y el crecimiento. Las principales contribuciones de este trabajo son la definición de indicadores que permiten identificar y clasificar las empresas de acuerdo a su capacidad de resiliencia luego de un evento extremo, así como la definición de un marco de referencia que incorpora los principales atributos que caracterizan a las empresas antifrágiles.

Los hallazgos de este estudio permitirán soportar a las empresas que deben enfrentan los retos de un ambiente VICA y están expuestas a riesgos

emergentes y eventos extremos, también conocidos como Cisnes Negros. Así mismo, el marco de referencia y los esquemas de medición propuestos permitirán fortalecer las disciplinas de gestión de riesgos y administración de empresas.

Palabras clave: Resiliencia, Antifragilidad, Resiliencia Organizacional, Opcionalidad, Yacimientos No Convencionales, Indicadores Riesgo-Desempeño.

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Table of Contents

ACKNOWLEDGEMENTS……VIII

ABSTRACT……IX

RESUMEN……X

TABLE OF CONTENTS……XII

LIST OF FIGURES……XV

LIST OF TABLES…… XVIII

LIST OF ABBREVIATIONS…… IXX

INTRODUCTION……1

Description of the Problem…… ……1

Research Questions and Goals …… ……7

Contributions and Related Publications……9

Research Methodology…… 12

Structure of the Thesis…… 15

1. BACKGROUND…… 17

1.1. Risk Management……17

1.2. Antifragility…… 24

1.3. Organizational Resilience……28

1.4. Risk-Performance Metrics……30

2. THEORETICAL FRAMEWORK FOR ANTIFRAGILE ORGANIZATIONS……33

2.1. Crisis Management Resilience Frameworks……33

2.2. Antifragile Theoretical Framework……36

3. UNCONVENTIONAL OIL AND GAS INDUSTRY……..……...40

3.1. Extreme events…….……..…42

3.2. Factory approach…….……..…. 44

4. CRITICAL FACTORS FOR COUNTRY UNCONVENTIONAL HYDROCARBON DEVELOPMENT…….....46

4.1. Global Unconventional Hydrocarbon Resources……..……..... …46

4.2. Factor definition……..……...48

4.3. Unconventional Development Index……..……49

4.4. Innovation……...…….…. 50

5. ANTIFRAGILE OIL AND GAS COMPANIES……...…..…….. 54

5.1. Metric definition……..……..……54

5.2. Resilience Measurement……...……..57

6. CASE STUDY RESULTS AND ANALYSIS FROM ARGENTINA……..…..... 65

6.1. Argentina UOG Landscape…….…..... 65

6.2. Tecpetrol…….……...67

6.3. Extreme Crisis Response……..…..... 71

6.4. Antifragile Attributes Grading……..……...…....72

7. CASE STUDY RESULTS AND ANALYSIS FROM COLOMBIA……..……...…76

7.1. Colombia UOG Landscape……..……...76

7.2. Drummond Energy……...……..… 79

7.3. ESG Practices……..……80

7.4. Antifragile Attributes Grading……..……..…… 88

8. ANTIFRAGILE FRAMEWORK PROPOSAL……..……... 91

8.1. Adaptative Strategies……..……..…..…..… 92

8.2. Antifragility Framework Validation and Development……..…..….98

8.3. Propositions, Casual relationships, and Hypotheses……..……..….. 101

9. CONCLUSIONS AND FUTURE WORK…… 103

9.1. Conclusions…… 103

9.2. Future Work…… 106

COMENTARIOS CON EL VISTO BUENO DEL DIRECTOR…… 107

BIBLIOGRAPHY…… 108

APPENDIX A. GLOSSARY…… 118

APPENDIX B. OIL AND GAS INDUSTRY INDICATORS …… 120

List of Figures

Pg.

Figure 1. Diagram with the research methodology and the steps and sources utilized... 14

Figure 2. Applicable risk management strategies based on uncertainty…..…….....……... 20

Figure 3. The ability of an organization to perform its missions……...……...…...… 24

Figure 4. Diagram of antifragile, resilient, and fragile systems…….……..…..... 25

Figure 5. Four-level Maturity Model for Organizational Resilience (MMOR)…..... 29

Figure 6. Performance Management and Risk Management……..…….. 32

Figure 7. Framework for Crisis Resilience……..……...……...… 34

Figure 8. Conceptual Framework for Resilience Engineering……..…...… 34

Figure 9. The architecture of System Resilience…….……..… 35

Figure 10. The Evolution of Resilience to incorporate Antifragility……..…….. 37

Figure 11. State of the art Organizational Resilience and Antifragility……...… 38

Figure 12. Oil industry antifragility response to 2014-2015 oil price downturn…….. 44

Figure 13. The learning curve in the Permian Region……...……..….. 45

Figure 14. Hydrocarbon reservoir classification……..…….....…... 47

Figure 15. Resilience level classification for UOG Global and Independent US companies in 2014……....60

Figure 16. Resilience level classification for UOG Global and Independent US companies in 2019…….…….. 62

Figure 17. Resilience level classification for Integrated and Independent Canadian firms…….…….62

Figure 18. Resilience level classification for UOG Latin American firms…….…..…...…..63

Figure 19. Best unconventional development project performers in Argentina…….....68

Figure 20. Project sorted by state entity participation and execution lead time…...…..… 69

Figure 21. Fortin de Piedra project evolution…….....….. 70

Figure 22. Tecpetrol's Expand and Abandon options……..…….…..…72

Figure 23. Five-step risk management approach to build trust and obtain the LTO in UOG operations…….…….…….....80

Figure 24. Drummond's Circular water management system……..……....…. 83

Figure 25. 5-year stock price comparison XOM, CVX, and NEE ……....…….....98

Figure 26. Organizational antifragility framework…….……...…. 101

List of Tables ... Pg.

Table 1. Countries with significant UHR potential current development status……. ….48
Table 2. Critical Factor and weights required for UHR development…….…….....….....49

Table 3. Unconventional Development Index (UDI) ranking for the 22 analyzed countries…….…….……..50

Table 4. Selected Resilience Indicators……..…….…….……...…55

Table 5. Peer Group companies and main relevant financial attributes……...…..58

Table 6. Tecpetrol's Resilience and Antifragility Attributes…….....….73

Table 7. Drummond's Resilience and Antifragility…….……..……...….88

Table 8. Adaptative Strategies and Tactics followed for oil and gas firms in North America…….……..…92

Table 9. Optionality showed for antifragile oil and gas companies in Latin America…….95

Table 10. Sustainability CO2 report from Canadian companies…….……..……...97

Table 11. Antifragility framework Attributes followed for IOG companies……...….. 99

List of Abbreviations

AbbreviationTerms

AHP	Analytic Hierarchy Process
ALARP	As Low as Reasonably Practicable
ANH	Agencia Nacional de Hidrocarburos (National Hydrocarbon Agency)
ANLA	Agencia Nacional de Licencias Ambientales (National Environmental Permit Agency)
ARM	Adaptive Risk Management
BACT	Best Available Control Technology
BCM	Business Continuity Management
CAGR	Compound Annual Growth Rate
CAS	Complex Adaptive Systems
CBM	Coal Bed Methane
CFFF	Cash Flow from Financing
EBITDA	Earnings Before Interest Depreciation and Amortization
EIA	Energy Information Administration
ERM	Enterprise Risk Management
GAGEP	Generally Accepted Good Engineering Practice
GHG	Greenhouse Gas
GII	Global Innovation Index
GDP	Gross Domestic Product
GyP	Gas y Petróleo del Neuquén
HSE	Health, Safety and Environmental
HRM	Holistic Risk Management
HRO	High-Reliability Organization

IRGC	Improving Governance of Systemic Risks
IOC	International Oil Company
JIT	Just-In-Time
KPI	Key Performance Index
LTO	Social License to Operate
MMRO	Maturity Model for Organizational Resilience
NOC	National Oil Company
NOG	Not-Governmental Organizations
ORRI	Overriding Royalty Interest
OS	Occupational Safety
POC	Provincial Oil Company
PRA	Probabilistic Risk Assessment
PSM	Process Safety Management
QM	Quality Management
ROE	Return on Equity
ROIC	Return on Invested Capital
S&P 500	Standard & Poor's 500
SCM	Supply Chain Management
TBL	Triple Bottom Line
UAE	The United Arab Emirates
UDI	Unconventional Development Index
UHR	Unconventional Hydrocarbon Resources
UOG	Unconventional Oil and Gas
US	The United States of North America
VUCA	Volatile Uncertain Complex and Ambiguous
YPF	Yacimientos Petrolíferos Fiscales

Introduction

Description of the problem

The Great Recession that began in 2007 alerted many executives of the gaps in their understanding and management of risk. Measuring risk facilitates decision-making, but risk management relies primarily on thoughtfulness and not necessarily complex models. The recession made evident the shortcomings of banks, which had models with plenty of math and statistics but little economic analysis. A simple qualitative analysis might have been more insightful than a sophisticated analysis based on irrelevant parameters (Koller, 2011, p. 183). The recession was a turning point for the risk assessment discipline, revealing that emerging risks, complex systems, and extreme events are impossible to model. The ability to make sound predictions and decisions based on such models is limited.

Today organizations have to deal with a series of emerging risks, extreme events like the Covid-19 pandemics, complexity involving supply chain disruptions, and high uncertainties characterized by lack of information and ambiguity about coming out events (Flage & Aven, 2015). Interconnectivity offers the possibility of improving efficiency at the expense of reducing resilience and increasing the likelihood of systemic risks, defined as those with the impact of breaking down the entire system. Complex Adaptive Systems (CAS) can incorporate organizational strategies like agility, flexibility, and options formulation to cope with systemic risks (IRGC, 2018).

Emerging risks, Black Swans, complexity, ambiguity, and extreme events are impossible to model since they do not have historical data. It impairs the ability to make predictions and make decisions based on their occurrence or the organization's strength to cope. For making decisions to handle such risks, people typically use the concept of the availability

heuristic. They assess the likelihood of risks by asking how readily examples come to mind, despite their substantial limitations.

With the awareness that these risks are impossible to predict, there is an increased need to identify succeeding organizations in VUCA environments. They should have implemented antifragile protective response strategies like adaptation, agility, resilience, flexibility, learning, and uncertainty recognition. In other words, the management to maintain high-level performance, focusing on minimizing loss of negative consequences and considering uncertainty as a key variable with potential damage and growth opportunities simultaneously.

Strong risk management skills are critical for resilience organizations and even more for antifragile ones, which should develop risk management processes for a wide variety of applications, including the ability to adapt to capture opportunities and promote learning and growth. Risk management should extend beyond safety-oriented built on quantitative risk analysis and tolerability/acceptance criteria. The risk assessment must evolve to address the existing and future challenges, including more complex systems, rapid innovations, sudden changes, and VUCA environments.

In recent years, after the publication of the book Antifragile, things that gain from disorder (Nassim Nicholas Taleb, 2012), the possibility to apply resilience strategies to risk management received higher impulse. The new concept aims to withstand an extreme event without affecting its overall results by learning, adapting, and improving its performance. The caveat is the lack of case studies involving real-life antifragile organizations. Nevertheless, researchers and practitioners are analyzing the concept even more after the Covid-19 pandemic impacts (Derbyshire & Wright, 2014) (Terje Aven, 2015a) (Martinetti et al., 2019) (De Smet, A., 2020).

No much literature and case studies are available, and as a start point, it is necessary to define and describe what an antifragile organization is. There is a lack of a theoretical framework required to support theory building from a research study (Derbyshire y Wright, 2014). From the several research needs addressed above, it is possible to conclude that the antifragility field is in its infancy (Kennon et al., 2015).

The importance of antifragility is the conceptual focus of strengthening the organization's capabilities to survive in VUCA environments, control surprise events and benefit from their occurrence. Taleb developed the concept of antifragility in a socio-economic context, not in industrial production; however, it may have its most significant practical utilization when applied to industrial environments. Structures, systems, processes, and cultures should evolve to make the organization more antifragile (Ghasemi & Alizadeh, 2017).

There is no clear definition of how antifragile organizations should behave and the main characteristics they should have. Nassim Taleb's proposals are a result of philosophical observations and mathematical relations not derived from empirical data. Today, there is no common understanding of an antifragile organization and which the best examples of such company behavior are. Nature offers multiple examples of antifragile systems after millions of years of adaptation (Terje Aven, 2015b). Organizations are trying to resemble nature and become antifragile to some extent. Although it is possible to think about processes to improve and become resilient, defining and describing an antifragile organization is challenging.

To overcome this limitation, we define a theoretical framework and performance indicators that help us select the companies serving as vehicles to explore the enterprise's key attributes and characteristics. We utilize the Unconventional Oil and Gas (UOG) industry environment as the testing room to identify the best performers thriving in a turbulent environment in North America and Latin America. We select the lapse between two extreme events suffered by the UOG industry in North America to test the concept. After having high costs, the sector evolved and obtained efficiency gains based on trial and error, evolving technology, and shared knowledge.

Global primary energy demand would rise by 1.3% each year to 2040 without considering the post-Paris Agreement. The share of fossil fuels in world energy demand was 81% in 2018, and with current policies, it reduces slightly to 79% in 2030 and 78% in 2040. Nations make permanent efforts to avoid depending on abroad to develop reliable sources of energy. The preferred alternative to satisfy this growth is natural gas, increasing participation in the energy basket. It is cleaner burning and reduces air pollutants and greenhouse gas (GHG) emissions than other fossil fuels. Consequently,

there has been a significant switch from coal to gas for electric generation, mainly in the US, Europe, and China.

Unconventional Hydrocarbon Resources (UHR) constitute an abundant and reliable source to satisfy the growing world energy needs. UHR is available in around 60 countries, and despite the challenges involved, at least 32 of them have started exploration and development activities conducted to exploit them (WANG et al., 2016).

The main benefits from UOG for a country are energy security, switching coal to gas for electricity generation to reduce GHG emissions, economic rent, new jobs, local enterprise opportunities, and improvement to society's general welfare. The drawbacks are local environmental and global clime effects, unequal distribution of risks and rewards, energy transition delay, and public controversy (Bravo & Hernandez, 2020b). The Analytic Hierarchy Process (AHP) is helpful to evaluate a country's decision to move toward UOG, which involves balancing the benefits and opportunities with the costs and risks involved. The decision to select exploiting shale gas compared to nuclear energy or maintain the prevalence of coal for electric generation in Poland constitutes an AHP comprehensive case (Adamus & Florkowski, 2016).

Commercial success occurs when International Oil Companies (IOCs) and National Oil Companies (NOCs) are keen to develop UHR, share best practices, and build a learning curve. It contributes to applying the best (Environmental, Social, and Governance) ESG practices, reducing costs, and increasing productivity, the only way to have profitable green exploitation. In the early 2000s, the return on capital for the IOCs was near 20%. In 2019 it was less than half that, considering the same level of hydrocarbon prices. As a result, the conditions to exploit UHR in the US and Canada harassed after 2019 because investors started to demand better equity returns, debt reduction, and increasing ESG commitment to obtain or boost their Social License to Operate (LTO). UOG companies started to switch their focus from growth to productivity and defined aggressive ESG goals to reduce GHG emissions and freshwater consumption.

Additionally, lower oil and gas prices fuelled by the increasing production, COVID-19 pandemic, and a lower world energy demand, together with restrictions to build new

infrastructure due to public protests, affected IOCs' financial results possibilities to invest in UOG development. The resilient firms were those with healthier balance sheets, lower debt, productivity, and diversified assets. Only a few of them had antifragile behavior and could grow production during 2020 despite all these challenges.

Governments should be aware of the increasing need to enforce environmental protection and lure IOCs investment to generate long-term returns for investors. Policymakers need to understand the critical factors required for successfully exploiting UHR, enforcing environmental protection, incorporating IOCs' requirements to invest, reducing and controlling the non-technical risks and uncertainties, and satisfying their possibilities to obtain a minimum profit. Such are Argentina, Chile, China, Oman, Saudi Arabia, the United Arab Emirates (UAE), and Bahrain, which invested in advance in exploration and infrastructure to become more attractive for IOCs and require improving ESG goals.

Many studies focus on the technological, environmental, or economic aspects of UHR development. Only a few assess the critical factors at the country level for UOG development. We go a step further and explore the critical factors for a nation to attain commercial UOG exploitation. We analyze the 22 nations that have pursued UOG development and the critical factors required to obtain commercial production through projects and final investment decisions from NOCs and IOCs. Antifragile firms are the ones with the ability and resources to execute the UOG development projects safely, fast, and involving optionality.

UOG and hydraulic fracturing have generated many discussions regarding benefits, costs, and tradeoffs for governments, companies, the environment, and society (Williams, 2015). Challenges and implications for risk assessment are discussed by (Terje Aven, 2017a). The expectation is that, by implementing new approaches for risk assessment, management, and communication, it will be possible to bring light to the debate regarding the convenience of hydraulic fracturing and provide new insights to the body of risk knowledge.

Hydraulic fracturing has sparked much debate regarding the risk tradeoffs and societal concerns associated with this technology and brought to light the need for open and timely dialogue between industry, government, research scientists, and community

members. The biggest challenge is public acceptance, the climate of distrust and skepticism that makes purposeful, productive communication close to impossible. Overall, the primary opposition relates to social and economic concerns rather than technological issues. Risk communication is critical. It is not clear how to best engage with key stakeholders in understanding the benefits, risks, and tradeoffs of energy development. Firms spend an extraordinary amount of time on misunderstandings or concerns that are not a top priority (Williams, 2015).

The challenges associated with hydraulic fracturing and its implications for risk assessment are summarized by (Terje Aven, 2017c):

1. Has the full spectrum of potential risks and benefits been identified and weighed?
2. What are the risk tradeoffs or countervailing risks?
3. How are potential risks and benefits distributed in the population?
4. What should broader social, economic, legal, and public policy issues be considered?
5. What are perceived risks and benefits, and how do these compare to actuals?
6. What is the best way to communicate risk/benefit information?

The discussion incorporating risk analysis limitations bring two essential ideas to the discussion:

1. It is not clear how to best engage with key stakeholders in understanding the benefits, risks, and tradeoffs of energy development.
2. Research on these topics, specifically looking into the hydraulic fracking case, could lead to more general ideas and findings that can benefit other situations; the case has a more broad impact on the risk analysis field.

Sound theories had been developed about organizational resilience, leading to organizational resilience definitions, attributes, and characteristics that contributed to defining several resilient organization frameworks. We utilize the Maturity Model for Organizational Resilience (MMOR) proposed by (Ruiz-Martin et al., 2018) to show the way organizations evolve from fragility to antifragility over time. Ruiz-Martin stresses the need to have future research aiming to develop a framework to understand how good the organization is dealing with turbulent environments, which constitutes a fundamental

reason for this study. She also suggests that the common framework should also include indicators and a scale to measure the antifragile organizational resilience capabilities to deal with VUCA.

There are strong parallels between performance and risk management, showing that both serve to meet or maintain a set of specific performance goals in the future while controlling sudden disruptions or slowly changing conditions. We adapt the performance-risk management hypothesis, intending to evaluate it utilizing the mixed-method research to demonstrate its relevance and applicability (Thekdi & Aven, 2016) (Thekdi & Aven, 2019). Hence, we built this research on the notion that it is possible to judge the level of antifragility by looking at the historical performance and using judgments of the system's robustness and its ability to learn and make improvements (Terje Aven, 2015b).

We demonstrate that the antifragility concept is in the early development stage from the above challenges and considerations. Hence, exploratory research helps open up the field and craft the first theoretical propositions. The mixed-method research offers the opportunity to shed empirical light on some theoretical concepts or principles. The lessons learned assume the form of working hypotheses, either defining new research or defining analytic generalizations that will contribute to abstract theory building (Yin, 2018, p.37).

Research Questions and Goals

The final goal of this study is to develop a conceptual, organizational antifragility framework. To achieve this goal, we defined the following objectives:

1. Identify the critical country factors required for unconventional oil and gas resource development.
2. Define a set of customarily performance-risk management indicators as proxies to measure and rank organizational antifragility.
3. Identify the Risk Management Techniques and Management Practices implemented for unconventional oil and gas antifragile companies.

In our case, the mixed methods research and the case study contribution to knowledge are merely exploratory. It looks for elaborating a new theory or identifying a new hypothesis, rather than confirmatory, for testing an extant hypothesis (Gerring, 2017,

p.40). That is why not defining a hypothesis as part of this study, and instead, we present a series of research questions and propositions.

Given the lack of research common to a new concept applied to the antifragility concept, it was necessary to address several research questions to help bring ideas and facts to develop analytic generalizations that can lead to greater insight. For that purpose, we propose the following research questions:

- How the environmental context shape the antifragility level of an organization?
- How to measure organizational resilience after a disruptive event?
- How to assess and measure the antifragile level of an organization?
- How can antifragile organizations be defined and identified?
- Which are the leading strategies and attributes that characterize an antifragile organization?
- How is the organizational culture of an antifragile organization?
- How effective is the skill transfer and communication among the organization's locations or subsidiaries?
- How are antifragile companies organized to cope with VUCA and disruptive events?

We formulate several qualitative subquestions, which, in turn, become specific questions used during the interviews to help to develop the interview protocol or guide (Creswell & Creswell, 2018, p.133). Hence, we set out an additional subset of questions specific to the oil and gas industry and the sector of unconventional oil and gas development:

- How oil and gas companies address the high uncertainties involved in unconventional reservoir development?
- Which are the most appropriate risk management tools to deal with high uncertainty and ambiguity in oil and gas operations?
- What is the level of effectiveness of the risk management tools utilized for oil and gas companies to address VUCA?
- Which performance and safety metrics can be used as a proxy to measure the antifragility level?

Research practice recommends formulating study propositions to facilitate the case study's scope definition, to contribute to the research design and data collection strategy (Yin, 2018, p.26). Accordingly, we established the following propositions:

- Antifragile organizations have better performance and risk mitigation results than their competitors.
- Among the main attributes that characterize an international antifragile organization is to have a flexible subsidiary, which may partner with the local NOC, adapt, and simultaneously reap the parent company's strengths.
- It is challenging to transfer antifragile organization skills among subsidiaries because of cultural differences and their uncertainties.
- Risk-performance indicators help identify antifragile firms and classify them according to their resilience maturity level, either fragile, robust, resilient, or antifragile.
- The literature and industry surveys available are helpful to build a theoretical framework to characterize antifragile organizations.
- Antifragile organizations generate risk management skills according to the uncertain environment they have to endure.
- Antifragile organizations must have a culture characterized by risk awareness, quality control, adaptation, and innovation.

Contributions and Related Publications

We presented the main contributions of this thesis for discussion at different conferences and journal peer reviews, as listed below:

- First attempt to provide empirical evidence to test the resilience and antifragile capabilities for organizations dealing with turbulent environments by studying firms' performance in unconventional oil and gas development in North America and Latin America during 2014-2020.
- An organizational antifragility framework proposal based on the literature and the most recent surveys and books published incorporating the Covid-19 pandemic Black Swan effects.
- An update of the hydrocarbon resources classification triangle includes energy, capital technology, and innovation issues.

- Identify the eight (8) most relevant critical development factors for UHR commercial development after considering the exploitation status in 60 countries, emphasizing the 22 most relevant.
- The Unconventional Hydrocarbon Development Index (UDI) model classify, ranks, benchmarks, and forecasts UHR development activity for any given country.
- An update of the general matrix for risk management strategy, including the uncertainty category, with antifragility, as a management strategy in pursuing opportunities.
- A five-step risk management approach proposal intends to help companies operate more safely and obtain the LTO after reviewing top performers' risk management strategies in Latin America. LTO is a concept that originated in the mining industry and is closely associated with trust and reputation. In Latin America, it concerns the level of acceptance provided by local communities and other stakeholders to companies pursuing development activities and depends on the overall acceptance and operational experience earned in a given region.
- An application of the holistic risk assessment approach incorporates interviews and observations of top industry performers in Latin America to identify best practices successfully implemented by such companies to counter ambiguity.

Published Papers

1. Bravo, O., Hernandez, D. (2021). Critical Factors for Unconventional Hydrocarbon Resources Development. Ciencia, Tecnología y Futuro - CT&F. (Accepted. In Press).
2. Bravo, O., Hernandez, D. (2021). ERSS-D-20-00997. Organizational Resilience Measurement after Disruptive Events: A Study of Unconventional Oil and Gas Enterprise Performance. Energy Research & Social Science. (Accepted. In Press).

Conference Papers

1. Bravo, O., & Hernandez, D. (2020). Risk Management Strategies Required for Unconventional Oil and Gas Exploration and Development in Latin America. SPE-199430-MS, 16. https://doi.org/10.2118/199430-MS.

2. Improving Environmental and Safety Risk Management for Unconventional Oil and Gas Development in Colombia incorporating best practices. Bravo, O., Universidad Nacional; Usuriaga, J., Ecopetrol; Casas, O., Ecopetrol; Cardona, J., Ecopetrol. Simposio Latinoamericano de Exploración y Desarrollo, ACGGP, 2018.
3. Revisión de Incidentes Ambientales en la Explotación de Yacimientos No Convencionales en Estados Unidos. Casas, O., Lombana, S., Usuriaga, J.M., Bravo, O., Cardona, J. Simposio Latinoamericano de Exploración y Desarrollo, ACGGP, 2018.
4. Water Management Alternatives for Hydrocarbon Production from Source Rocks in Colombia, Usuriaga, J., Ecopetrol; Bravo, O., Ecopetrol; Casas, O., Ecopetrol; Cardona, J., Ecopetrol. Simposio Latinoamericano de Exploración y Desarrollo, ACGGP, 2018.

Conferences

1. What is the Proper Approach for Risk Management in Unconventional Operations? Bravo, O., Universidad Nacional de Colombia. SPE Workshop: Challenges to Develop Unconventional Resources in Colombia, 28-29 March 2019. Bucaramanga, Colombia.
2. Esquemas de manejo de Riesgos Operacionales, Ambientales y sociales en proyectos de YNC, Bravo, O., Colombia Petróleo y Gas, 10-11 July, 2019. Bogotá, Colombia.
3. Critical Factors for Unconventional Hydrocarbon Resources Development. International Congress and Exhibition Colombia Oil & Gas. April 30th, 2020.
4. Análisis del Auge y la Crisis de la Industria Petrolera de 2015 a 2020, June 18th, 2020, Elite Training, Webinar.
5. Critical Factors for Unconventional Hydrocarbon Resources Development. Colombia Oil & Gas online 2nd Online Business Congress. Session 3.2. Untapping Unconventional Resources. July 23th, 2020.
6. SPE-199430-MS Risk Management Strategies Required for Unconventional Oil and Gas Exploration and Development in Latin America. SPE HSE International Conference. July 30th, 2020.
7. Determinación del nivel de resiliencia de las empresas petroleras dedicadas a la explotación de Yacimientos No Convencionales en Norteamérica y Latinoamérica. 3th Congress and Exhibition Colombia Oil & Gas. 21 - 25 June 2021.

8. Proposal for Organizational Antifragility Measurement through Unconventional Oil and Gas Enterprise Performance Analysis. SPE Trinidad & Tobago - 2021 Energy Resources Conference. 28 - 30 June 2021. Invited Presenter (IP).
9. Determinación del nivel de resiliencia de las empresas petroleras dedicadas a la explotación de Reservorios No Convencionales en América del Norte y América Latina. Colombia Petróleo y Gas 2021. 21 – 25 June 2021.

Research Methodology

In Sections 1.1 and 2.2, we present the concept of antifragility, stressing that the field is in its research infancy, and a lack of articles, theories, and real cases are a certainty. During this early development stage, exploratory research helps open up the field and craft the first theoretical propositions (Seuring, 2011).

The main obstacle in case-based research is that it relies on a minimal number of cases, often just one. Additionally, there is neither definition nor criteria to define and select antifragile organizations in the literature. It is difficult to pinpoint a specific organization that can be useful to evaluate the level of antifragility has exhibited before and after a disruptive event has occurred. We utilize the constructivist approach for the design of the case study and the multi-method analysis research to capture the opinions and perspectives of different actors and studies, to bring to light the truth for the antifragility organization's realities. Constructivism or social constructivism is an approach characteristic of qualitative research (Creswell & Creswell, 2018, p.7).

A case study or Small-C study is an intensive study of a single case or a small number of cases, which promises to shed light on a larger population of cases. A multi-method or mixed-method approach is beneficial for theory building since it allows one to overcome the disadvantages of any single research method (Bryman, 2007). The definition of multi-method or mixed-method is of a Small-C and Large-C analysis combined in a single study or research stream (Gerring, 2017, p.36). In our study, given the limited number of companies available to conduct the analysis, we prefer to replace the term Large-C with Medium-C analysis to offer more accuracy. The series of comparisons and contrasts between Small-C and Medium-C research shed light on the information obtained and the

propositions' validation. Hence, we selected the multi-method case study to conduct this study to overcome the case study research's perceived weaknesses.

The case study research's epistemological orientation appears orientated toward the realistic perspective, which assumes a single reality independent of any observer. Nevertheless, given the flexibility of the methodology, the different perspectives captured from different observers, and the different work experiences from the author, the relativist perspective will be utilized to allow the recognition of multiple realities and having multiple meanings, with findings that are observer-dependent (Yin, 2018, p.16). The final goal will be to find casual inferences from the case study and multi-method evidence, transforming the observations and propositions based on hypotheses structuring, as proposed on the main objective.

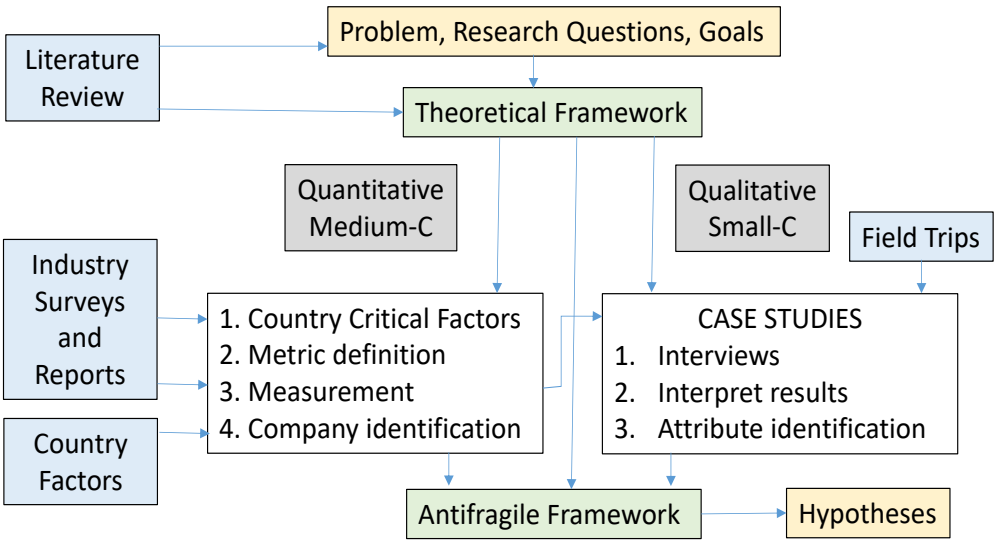
Following the typology of case selection proposed by Gerring, the case study research aims to causal inference. Its primary goal is to identify hypotheses and propositions, it is Exploratory, and for this study, it is Extreme. This type of case design maximizes variation in the variable of interest, which is Performance for this research. Organizations that are either incredibly successful or failed are more informative than average ones but pose a potential generalizability problem. Researchers want to evidence the causal effects and how they are generated by what mechanism(s). The last is essential to building theory, which is to generalize beyond the sample, extend the results to new topics, and connect it with extant research (Gerring, 2017, p.148).

Figure 1 illustrates the different stages and sources utilized in this study. The working hypotheses are a result of following the depicted steps. As seen, we complement the multi-method research with other strategies such as Literature review, Industry Surveys and Reports, Fieldtrips, and Qualitative Observations.

First, we follow the literature review for resilience and extreme events to build a theoretical antifragile framework to portray such organizations' main aspects. To understand how each country's environment affects firms' behavior, we identify and prioritize UHR development's relevant factors. Then, we define and try several custom metrics to select and rank antifragile companies. After, we analyze and compare the selected companies in North America and Latin America by contrasting and determining

the main strategic and organizational attributes, management skills, tools required to control risks and take advantage of the intrinsic opportunities.

Figure 1. Diagram with the research methodology and the steps and sources utilized. Source: the authors



The selected customarily financial and operational metrics are helpful to measure the organizational resilience maturity level after a disruptive event. We evaluate a series of financial and operational performance-risk indicators and select the most appropriate to classify the companies according to their resilience level of evolution. Following the above criteria, in this study, the companies analyzed with different level of detail are:

- Small-C analysis: Tecpetrol (Argentina) and Drummond Energy (Colombia).
- Medium-C analysis: 77 companies in the United States (50), Canada (24), and Latin America (3); 51 mergers and acquisitions, and 26 firms that filed for chapter 11 protection during 2015-2020, which belong to the UOG exploration and development sector. Additionally, we assessed the performance of 24 organizations in Argentina (18), Colombia (5), and Chile (1).

For bounding the Small-C case study research, the data collection and analysis encompass two firms exhibiting the lowest time among their peers to develop specific unconventional projects from the moment announced to its completion. The projects to be studied are:

1. Tecpetrol: best performer in Argentina, Vaca Muerta Basin. Fortin de Piedra development project, executed during 2017 and 2018.
2. Drummond Energy: best performer in Colombia, Cesar-Rancheria Basin. Caporo Norte development project, the first phase implemented during 2018.

We performed a series of interviews, industry reports analysis, and field trips to document the Qualitative Observations. The field visit list is the next:

- Drummond Energy, La Loma, Colombia, June 2018.
- Tecpetrol and Total, Vaca Muerta, Argentina, November 2018.
- PetroSkills Conclave, Houston, the United States, January 2019.
- ExxonMobil (XTO), Oklahoma, the United States, February 2019.

The companies with employee interviews:

- IOCs: Tecpetrol, Drummond Energy, Total, ExxonMobil, and XTO.
- NOCs: ENAP-Sipetrol and Ecopetrol.
- Service companies: Halliburton, Weatherford, and Schlumberger.

Structure of the Thesis

We organized the rest of this thesis as follows:

- Chapter 1: theoretical background supporting the research. The three funding theories require empirical data demonstration: antifragility, resilience maturity level, and the relation between risk management and performance.
- Chapter 2: Antifragile Theoretical Framework definition from the literature review. A review of the CAS, resilience, antifragility state of the art, and industry trends after the Covid-19 pandemic defines the reference framework to perform the mixed-method research.
- Chapter 3: the unconventional oil and gas industry and the extreme events which are framing this study. A review of the UOG industry characteristics and trends in North America offers the lab test to evaluate antifragility and resilience maturity among the top UOG players.
- Chapter 4: critical country factor definition for UOG development. We analyze the reasons and the main aspects a nation has to address to obtain commercial

production. The proposed UDI allows to evaluate and benchmark among the nations involved in UOG exploitation, offering a convenient way to evaluate the possibilities of success for a given country, considering those critical factors.

- Chapter 5: metric selection for resilience measuring after an extreme event. We define specific financial and operational outcomes to measure organizations' resilience after an extreme event. The metrics are helpful for ranking and selecting antifragile Unconventional Oil and Gas (UOG) companies for different countries.
- Chapter 6: Tecpetrol, a case study in Argentina. A review of the specific country uncertainties, the project scope, and the main antifragile attributes we observed.
- Chapter 7: Drummond Energy, a case study in Colombia. A review of the specific country uncertainties, the project scope, and the main antifragile attributes we observed.
- Chapter 8: Antifragile Framework and hypothesis definition. The framework incorporates the main common aspects of antifragile organizations: strategy, attributes, culture, infrastructure, and managerial skills. We test defined propositions to generate working hypotheses.
- Chapter 9: Conclusions and Future Work.

1 BACKGROUND

1.1 Risk Management

There are two views to the origins of uncertainty, namely ontological and epistemological randomness. The former results from quantum mechanics developed in the early 1900s and argued that the causes of events are impossible to trace. Consequently, making predictions cannot be a course of action. The latter came after introducing Laplace's scientific determinism in 1814 and argued that events are a consequence of specific causes. Once identified, one can assess, model, and forecast related risks and impacts (Derbyshire & Wright, 2014).

As a result, the epistemological organizational risk assessment incorporates a combination of fact-checking and managerial judgment. Decisions should be 'risk-informed' instead of 'risk-based,' generate a collective understanding, and identify, evaluate and define acceptable solutions, an approach also known as 'support adaptive' (risk-assessment informed). The ontological view concerning evaluating deep uncertainties considers both precautionary (emphasizing robustness and resilience) and deliberative (communication as a means to build trust) approximations.

Probabilistic Risk Assessment (PRA) is a set of reliable epistemological tools for assessing and evaluating risks in engineered systems but are less useful in circumstances with little knowledge (Shortridge et al., 2017). One weakness of the PRA approach is the human propensity to define and over-emphasize chains of cause-and-effect, denominated 'narrative fallacy' (Taleb, 2010, p.62). By contrast, in the ontological view, outcomes result from stochastic processes not connected to causation.

Mining, nuclear, petrochemical, plastics, oil, and gas, among other industries, face social pressure and countless attacks from social media and nonfactual news that negatively affect their future development. Companies in such industries require implementing resilience strategies as an alternative way to conduct a risk assessment to allow systems to maintain functionality and effectively recover from disruptions and handle uncertainty.

The ontological view is mandatory for emerging risks, as climate change and VUCA. The concept of emerging risks arose to name large-impact, hard-to-predict, and rare events beyond the realm of regular expectations, what Nicholas Taleb calls 'Black Swans' (Taleb, 2010). They may impact the organization and multiple situations across geographic borders, industries, and sectors in ways difficult to imagine. Emerging risks and black swans are not the same, although they are complementary. The first is related to known unknowns and the former to unknown knowns, unknown unknowns, and a subset of known knowns. Probabilities and risk measurements are impossible to apply. To determine the best path to avoid such risks, people tend to use what denominated the 'availability heuristic': use recent experiences, especially short-term ones, apply the same logic, and expect similar consequences (Thaler & Sunstein, 2009, p.32).

There are three main strategies for risk management: risk-informed, cautionary/precautionary, and discursive. The risk-informed approach base on assessments founded on probabilities, scenarios, and cause-effect definitions. The precautionary approach focuses on building either robustness, resilience, or antifragility. The discursive or deliberative approach promotes communication and transparency to build trust and risk weights against relevant benefits.

Adaptive risk management arose as an alternative based on the central idea is that as uncertainty is pervasive, one optimal management choice is not achievable. Instead, there could be a range of often competing decision alternatives, which tracks dynamically to gain information and knowledge about the system and the effects of different courses of action (Bjerga & Aven, 2015). As the different alternatives evolve, there is an increase in the knowledge about the phenomena. It is then possible to obtain a narrower, higher probability interval, which facilitates the decision-making process.

Additionally, the IRGC developed discursive or deliberative management tools and case studies named Risk Governance Framework (IRGC, 2017). They focus on effective and early communication to create long-term trust in risk management, particularly for VUCA. Most organizations lack the capabilities to design and implement effective risk management strategies that assess plural values and interests and communication to relevant stakeholders. Those social needs should be integrated into engineering thinking when assessing those risks and comprise other resilient organizations' characteristics.

For emerging risk, characterized by weak knowledge, risk management may suggest a cautionary or precautionary strategy due to the difficulties to specify consequences and the things humanity values. (Flage & Aven, 2015). The cautionary principle is used for all uncertainties and ambiguities, while the precautionary principle is in scientific uncertainties. The cautionary principle defines that in the face of uncertainties, caution should be a ruling principle. The precautionary principle states that in the case of a lack of scientific certainty about an activity's possible consequences, the activity should not be executed, or measures should be implemented to reduce the risk. However, too heavy reliance on such a strategy could restrict development and innovation. The risks must always be weighed against the relevant benefits (T. Aven, 2014, p.170).

An important aspect to consider before any strategy is selected is establishing the level of knowledge and uncertainty regarding a specific situation. Risk reduction strategies are recommended when risk analysis yields accurate forecasts and determines event causes with some degree of confidence. When knowledge is limited, using either a cautionary or a precautionary approach is suggested due to the difficulties in determining consequences and the utmost importance to society. The cautionary principle is used for all kinds of uncertainties and ambiguities, while the precautionary principle is in cases of scientific uncertainties. However, overreliance on this strategy could restrict innovation and development (Flage & Aven, 2015).

Based on the level of uncertainty, risk management strategies divide into four categories: risk-informed, robustness, precautionary, and resilience (T. Aven, 2014, p.164) (Terje Aven, 2016), as follows:

- Small uncertainties: risk assessments, cost-benefit analysis, technical standards, education, economic incentives, and voluntary agreements.

- Moderate uncertainties: ALARP (As Low as Reasonably Practicable), BACT (Best Available Control Technology), high-performance standards of barrier systems, redundancy, and diversity in designing safety devices, containment, and improving coping capacity.
- Deep uncertainties: broad risk characterization, diversity, avoiding high vulnerabilities, flexible responses, and adaptation.

The IRGC updated the above strategies to incorporate ambiguity, recognizing the need to generate tolerance and mutual understanding of conflicting views concerning risk impacts and benefits from the different stakeholders involved (IRGC, 2017). We add the uncertainty category named 'Opportunity' to reflect the upside risk. It includes the possibility to incorporate optionality and antifragility as alternatives to enhance resilience by improving performance, adaptability, and sustainability. Figure 2 summarizes the applicable risk strategies according to the uncertainty category and knowledge (Bravo & Hernandez, 2020b).

Figure 2. Applicable risk management strategies based on uncertainty. Source: adapted by the authors, 2020.

		Uncertainty Category				
		Conventional	Complexity	Deep Uncertainty	Ambiguity	Opportunity
Risk Strategy	Management	Risk Reduction	Robustness	Resilience	Discursive based	Antifragility
	Assessment	Routine-based	Risk-Informed	Cautionary / Precautionary	Risk-Informed	Optionality Performance
	Main Tools	- Regulation - Education - Best Practices	- Containment - ALARP - BACT	- DRR - Adaptative RM - HRO	- Communication - Holystic RM - TBL	- Real Options - Portfolio - KPI
Features	Knowledge	Strong	Medium	Weak	Frail	Weak
	Predictions	Accurate	Reliable	Inaccurate	Imprecise	Inaccurate

Antifragility = Resilience + Performance Improvement + Optionality

ALARP: As Low As Reasonably Practicable; BACT: Best Available Control Technology; DRR: Disaster Risk Reduction

HRO (High Reliable Organizations): preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience and deference to expertise.

KPI: Key Performance Indicators

RM: Risk Management; Risk-Informed alternatives: avoidance, reduction, transfer and retention.

TBL: Triple Bottom Line approach to address current Environmental, Social and Governance (ESG) requirements

We describe the most common risk management tools depicted in Figure 2.

- ARM is utilized in situations with deep uncertainty and limited knowledge, wherein the possibility of determining the best alternative is not plausible. A step-by-step

trial and error approach is required to select the most appropriate course of action and acquire knowledge (Bjerga & Aven, 2015). As the different alternatives evolve, a higher level of knowledge about a situation is obtained, making it possible to get a narrower, improved probability interval, facilitating the decision-making process.

- Holistic Risk Management (HRM) helps assess Health, Safety, and Environmental (HSE) risks and how stakeholders perceive them. Generally speaking, perceptions positioned higher than reality due to a lack of experience and knowledge from society (Torres et al., 2016). Risk assessment and mitigation should consider expectations instead of internal company analysis (Plattner et al., 2006). HRM stress that cost-benefit analysis should be applied to determine optimal ways to reduce risk perceptions to an acceptable level for all the parties involved. Evaluation of the internal and external factors that influence risk perceptions of UOG development in China (Huimin Tan, Jianhua Xu, 2019). Other examples of HRM applications exist in the oil and gas industry (T. Aven & Kristensen, 2005) (Torres et al., 2017) and (Torres et al., 2018).
- The Triple Bottom Line (TBL) approach for sustainable development is rarely applied in the oil and gas industry, despite the growing need for ESG performance improvement and increased interest in the energy-water nexus for energy production and energy used for water treatment and transport (Casey et al., 2017). Research examples of TBL for the mining and oil and gas industries, and alternatives to quantify the social and environmental dimensions to optimize shale gas energy systems in (Bond, 2014), (Rodger & George, 2017) and (Gao & You, 2017b).
- Portfolio management is a regular practice in UOG firms to diversify risk and gain access to knowledge or land access to different areas. There is a complete description of the processes and instruments for diversification and real options for the oil and gas industry (Bravo & Sanchez, 2012, p.247).

Risk assessment, management, and communication are evolving to provide organizations with more reliable tools for addressing new challenges to cope with VUCA, emerging risks, and extreme events. Climate change, artificial intelligence, cyber-physical systems, innovations, social unrest, political differences, supply chain interrelationships, terrorism, claim for action, and active and adaptive responses. These risk sources are inherently

uncertain, thereby challenging to analyze and model to develop the sound predictions required for decision-making.

Over the last 15–25 years, we have seen a shift from narrow perspectives for risk assessment based on probabilities, which struggle to describe and assess unfolding uncertainties, to new ways of thinking where events, consequences, uncertainties, knowledge, and effective communication are the base for risk analysis. There is a recent change from risk assessment approaches based on probabilities, which fail to describe and assess unfolding uncertainties and their causes, to new ways of thinking wherein endurance, uncertainties, complexity, knowledge, and effective communication are the basis for risk analysis. Risk models based on probability are challenging to build and test, given the low level of knowledge and understanding of events (Terje Aven, 2012).

A combination of qualitative and quantitative approaches is necessary to address the lack of reliability of such models. Current risk research to overcome these weaknesses focuses on (Terje Aven & Renn, 2015) (Terje Aven, 2018) (Zio, 2018):

- Measurement of risk, uncertainty, and resilience.
- Variation in risk perception among individuals.
- Effective risk communication.
- Proper use of the precautionary principle.
- Comparison of benefits, risks, and tradeoffs.
- Measurement of organizational safety mindfulness.
- Engineering thinking and resilience in extreme events.
- Impact of social media communications in operations and emergencies.

These hazard sources are uncertain, difficult to describe, and model quantitatively to offer the sound predictions required for decision-making. As a result, research focuses on organizational resilience and business continuity, simulation of accident scenario identification and exploration, and dynamic and condition monitoring-based risk assessment (Zio, 2018).

An alternative to risk assessment is implementing resilience strategies to maintain functionality and effectively recover from disruptions. The concept of system resilience is

essential and very popular over the last few years. There are four accepted ways to define resilience (Woods, 2015):

1. Rebound from trauma and return to equilibrium.
2. Synonym for robustness.
3. The opposite of brittleness.
4. Network architectures that can sustain the ability to adapt to future surprises as conditions evolve.

Scholars have demonstrated its application to engineering antifragile systems, designing cognitive cyber-physical systems that can learn from their experience, adapt to unforeseen events they face, and grow more robust in the face of adversity (Jones, 2014). It resembles the real options approach that arose several years ago, with lots of documented cases, several of them in the oil and gas industry (J. Mun, 2015). The challenge is to demonstrate that antifragility can be measured and applied successfully to organizations (Kennon et al., 2015). A research gap after recent theoretical works is to find a heuristic test to measure organizational resilience and time to recovery after a disruptive event, incorporating the antifragility concept (IRGC, 2017) (Ruiz-Martin et al., 2018) (Passos et al., 2018).

As seen above, most of the new risk management and scenario planning tools are developed based on the current process's inadequacy to determine a set of causes and formulate proper solutions. Additional tools that risk management should address in the following years (Zio, 2018):

1. A practical method to incorporate safety mindfulness, an operational behavior involving autonomy and responsibility. A proactive response is a form of ARM required before up-to-date information.
2. 'Engineering thinking in Emergency Situations' utilization, or the ability to create and implement effective engineering strategies on the fly, and the capability for resilience in the aftermath of accidents beyond design basis.

Engineering thinking in emergency situations offers a recent approach to fulfill ESG expectations. It emphasizes adaptability and resilience within organizations, incorporating abilities such as creating new temporary and adaptive organizational structures, moving from normal state to innovative mode quickly, and integrating the social dimension into

engineering activities in emergencies (Zio, 2018). Oil and gas, mining, nuclear, petrochemical, and plastics, among other industries, face social pressure and countless attacks from social media and fake news with effects on the operation and challenges to respond to the technical systems. Zio points out the need to integrate these aspects in the risk and resilience assessment and management to become more necessary and require effective integration of different disciplines and competencies, which involves developing new methods and approaches.

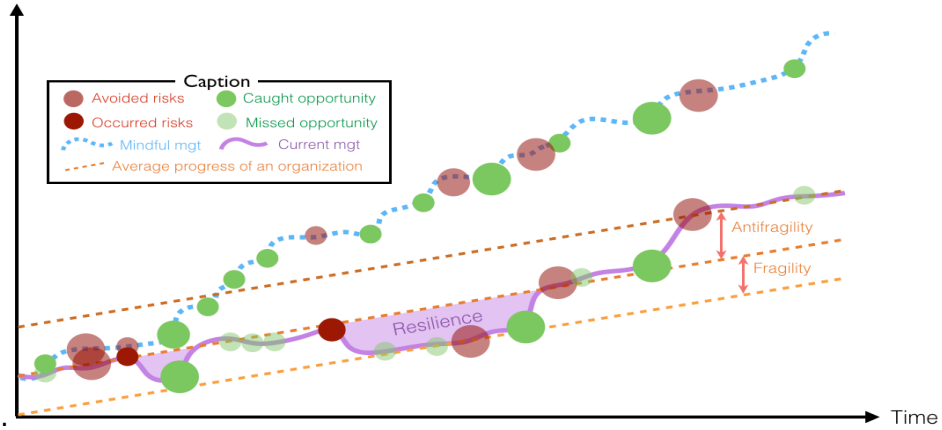
1.2 Antifragility

"Wind extinguishes a candle and energizes fire" (Nassim Nicholas Taleb, 2012).

Nassim Nicholas Taleb initially described the antifragile concept. Antifragility refers to systems that increase capability, resilience, or robustness due to mistakes, faults, attacks, or failures (Lichtman et al., 2018). One of the key concepts emerging from the seminal book Antifragile (Taleb, 2012) is that preparation for an uncertain future does not require causal constructions. According to Taleb, prediction and risk management should replace by processes moving us from fragility to antifragility, which represented an essential contribution to the practice of risk analysis.

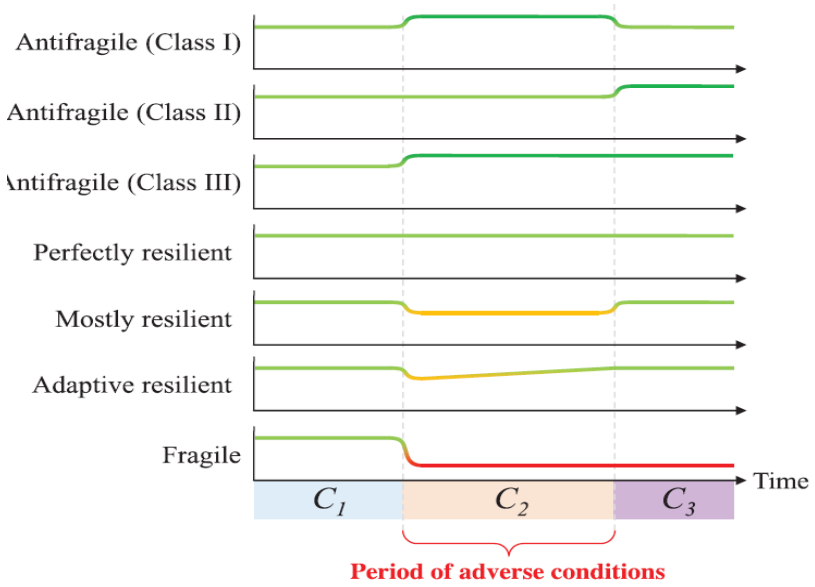
In an antifragile system, when extreme events occur, the impacts are only beneficial. The frequency distribution of outcomes places heavy weight on large positive values, with limited downside while having exposition to upside risk. In an enterprise context, those systems are rare and not studied in depth. Figure 3 depicts how the antifragility concept adds the idea of linking variation, uncertainties, and risk at the stress level to the positive and negative risk related to future behavior and an increase in organizations' performance (Benaben et al., 2019).

Figure 3. The ability of an organization to perform its missions. Source: Benaben et al., 2019.



According to how the increase in performance happens, three classes of antifragility exist, as seen in Figure 3 (Lichtman et al., 2018). Class-I antifragile systems increase performance during an attack, but the antifragile gain does not persist once the attack ends. On the other hand, class-II systems increase after the attack (usually due to information obtained during the attack). Class-III systems represent a mix of Class-I and II, in which the antifragile gain occurs at the beginning of the attack and persists after the attack ends. Antifragile systems can maintain objective performance through adverse conditions and achieve better performance during or after it.

Figure 4. Diagram of antifragile, resilient, and fragile systems. Source: Lichtman et al., 2018.



Other research has discussed how antifragility is also helpful for high complexity and uncertainty situations without a Black Swan trigger them. A strong interaction of failure activities in megaprojects can lead to catastrophic outcomes and are not a single event. It is then possible to detect early warning signals and proactively handle those risks through learning and knowledge management (Hajikazemi et al., 2016).

Antifragility embodies the chance of withstanding an extreme event without affecting the organization's overall results and learning, adapting, and improving its performance in the process. Antifragility incorporates optionality, hormesis, nuanced risk-taking, and redundancy as management tools for companies to capture the underlying opportunities within uncertainty and position them to adapt and grow.

A second important characteristic of antifragility is the shift in risk management's conceptual focus to protect from events instead of obtaining benefits from their occurrence. There is no theory or framework to explain and predict the way companies should behave. Taleb only defined a series of sub-concepts to deal with uncertainty: 'Optionality,' 'Controlling the dispersion of outcomes,' 'Barbell strategy,' 'Hormesis,' 'Redundancy,' and 'Small-scale experimentation' (Taleb, 2012) (Derbyshire & Wright, 2014). Next, there is a brief explanation of those sub-concepts:

1. **The value of creating optionality.** It is a concept previously described in the real options reasoning proposed by Myers in 1977. Taleb presents it as Convexity, where potential losses are limited, but potential gains are exponential. Increasing optionality is analogous to building 'flexibility' into the organization and its range of real options. It represents a shield against fallibility in predicting the cause of events and forecasting their outcomes (Taleb, 2012, p.173).
2. **Control the dispersion of outcomes.** Position the activities of the organization to minimize any downside risk through a protective floor. Simultaneously, take advantage of volatility in potential positive outcomes, making uncertainty beneficial rather than traumatic.
3. **Barbell strategy.** The dispersion of outcomes can be controlled by adopting barbell strategies (Taleb, 2012, p.161). It resembles the real option to abandon, focusing on taking no risks in areas subject to potentially large-scale adverse outcomes and, in

contrast, taking a lot of small risks in areas subject to potentially large-scale positive outcomes.

4. **Hormesis.** It is defined similarly as inoculation as a small dose of a harmful substance beneficial to the organism (Taleb, 2012, p.37). Organisms' exposition generates resistance to toxins to overcompensate its response, thereby building immunity to future exposure. In organizations, 'hormesis' is similar to the stress from uncertainty, peer review, complex project execution, or the need to achieve a goal or a performance indicator. A removal or absence of stressors can be detrimental, even if it seems beneficial in the short term. Similarly, any attempt to remove variation and error may weaken the organization and hinder adaptation and innovation.
5. **Redundancy.** Possibility to gain from opportunities when the organization has resources and skills available can be utilized in new situations when competitors are not ready, possibly because they follow a just-in-time or enterprise-resource planning strategy. Under the antifragile approach to uncertainty, efficiency is synonymous with Fragility. In project management, removing slack in delivery dates for the individual tasks comprising an overall project can result in almost every aspect of the project lying on the 'critical path,' making the project vulnerable to any risk event.
6. **Small-scale experimentation (trial and error).** Uncertainty does considerably less damage when distributed over time than when concentrated (Taleb, 2012, p.91). It implies that organizations should break up investments into small-scale experiments that test the market before committing to larger-scale investments. Also, running several small-scale business units producing different products rather than a single unit producing one may result in greater antifragility, despite the lower productivity.

According to the MMOR, a Fragile organization collapses and is not able to withstand changing environments. A robust organization can survive some set of changes in the environment. However, if those changes are outside the designed parameters, the organization will probably collapse. A resilient one is not only robust, but it is also able to survive unforeseen events. An antifragile organization can survive but and prosper or thrive in turbulent environments.

After a detailed literature review where 110 works that address different models and frameworks were analyzed, Ruiz-Martin also outlines the main attributes that characterize resilient organizations: Situation awareness, Managing organization's vulnerabilities,

Having resources, Improvisation capacity, ability to anticipate events, Agility, Learning individuals, Resilient capacity, Collaboration, Flexibility, Robustness, and Redundancy (Ruiz-Martin et al., 2018).

Ruiz-Martin also recommends that future research lines should aim to identify paths to develop resilient and antifragile organizations. Following this research line, she proposed to apply the Viable System Model to design resilient organizations. This research area has just started its development, and more theoretical and empirical research is needed. In line with the above, the antifragile organization framework should recognize those attributes. Additionally, evaluate and include others to complement them to reflect those enterprises' behavior eager to capture opportunities from stagnant competitors or the turbulent markets.

1.3 Organizational Resilience

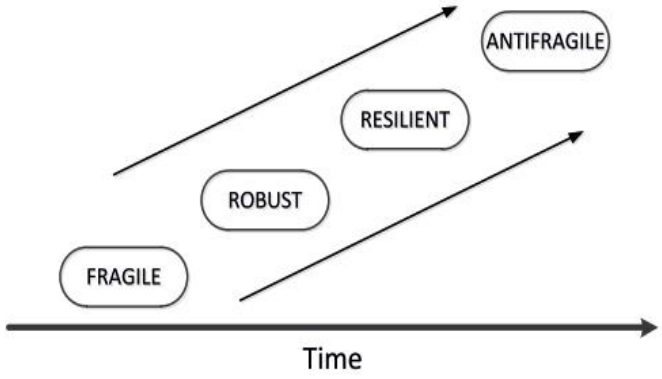
There are many definitions of resilience. The fundamental idea is that resilience represents the system's ability to withstand a significant disruption within acceptable degradation parameters and recover within an acceptable cost and time. At the organizational level, resilience is defined as the measurable combination of characteristics, abilities, capacities, or capabilities that allow an organization to withstand known and unknown disturbances and still survive (Ruiz-Martin et al., 2018). A related concept is Business Continuity Management (BCM), which refers to the organizational resilience to protect the interests of the key stakeholders, reputation, brand, and value-creating activities (ISO, 2012). A list of the terms from the literature that we utilize the most is in Appendix A.

An important caveat is that risk management differs from resilience management. The last can be conducted without considering risk. Having redundancy in the system may be an effective resilience management strategy, and it does not require assessing specific events and associated risks to be implemented. Resilience management does not need to know what events can occur or estimate their likelihoods as required in traditional risk assessments. Hence, it avoids the limitations of generating reliable probability estimates in situations with large uncertainties, for instance, for complex systems, where surprises could occur (Terje Aven, 2017b).

The IRGC Resource Guide for Resilience stresses the need for resilience strategies implementation. It differentiates between risk and resilience management fields, stating that resilience can, to some degree, be analyzed and managed without considering risk analysis. For instance, it is possible to improve the immune system through proper training without thinking about risk. The resilience-based approach allows decision-makers to put a more considerable emphasis on managing system performance to confront potential surprises and unforeseen events (Trump et al., 2018).

Under the four-level Maturity Model for Organizational Resilience (MMOR), depicted in Figure 5, the organization's resilience can be either Fragile, Robust, Resilient, or Antifragile. The degree of organizational resilience evolves from Fragile to Antifragile or vice versa, depending on its resources and capabilities (Ruiz-Martin et al., 2018). The MMRO constitutes the theoretical backbone of this study.

Figure 5. Four-level Maturity Model for Organizational Resilience (MMOR). Source: Ruiz-Martin et al. (2018).



According to the MMOR, a Fragile organization collapses and is not able to withstand changing environments. A robust organization can survive some set of changes in the environment. However, if those changes are outside the designed parameters, the organization will probably collapse. A resilient one is not only robust, but it is also able to survive unforeseen events. An antifragile organization can survive but prosper or thrive in turbulent environments (Ruiz-Martin et al., 2018).

After a detailed literature review where 110 works that address different models and frameworks were analyzed, Ruiz-Martin also outlines the main attributes that characterize resilient organizations: Situation awareness, Managing organization's vulnerabilities, Having resources, Improvisation capacity, Ability to anticipate events, Agility, Learning individuals, Resilient capacity, Collaboration, Flexibility, Robustness, and Redundancy.

Ruiz-Martin also recommends that future research lines should aim to identify paths to develop resilient and antifragile organizations. Following this research line, she proposed to apply the Viable System Model to design resilient organizations. This research area has just started its development, and more theoretical and empirical research is needed. In line with the above, the antifragile organization framework should recognize those attributes. Additionally, evaluate and include others to complement them to reflect those enterprises' behavior eager to capture opportunities from stagnant competitors or the turbulent markets.

1.4 Risk-Performance Metrics

Antifragility and high performance are closely related. The way the antifragility concept adds to managerial and risk analysis practices compared to robustness and resilience links variation, uncertainties, and risk at the stress level to the positive and downside risk related to future performance (Terje Aven, 2015b). Since 'hormesis' incorporates the need for organizations' stressors to improve and thrive under deep uncertainties, it is essential to define the proper metrics to measure and relate performance and antifragility.

An early attempt to measure resilience utilizing the Iceberg Theory was presented by (Jackson, 2007). This theory stands that the lack of resilience can be predicted through the statistical correlation between minor events and significant accidents and the incidence of small defects called near misses. The notion of Enterprise Risk Management (ERM) stresses the need for organizational performance management. ERM is not about minimizing an organization's risk exposure; it is the opposite: it is about exploiting risk for maximum competitive advantage. Aven and Thekdi built over these concepts to recommend using risk-performance indicators and giving weight to vulnerabilities, resilience, and antifragility.

Another approach to measuring resilience to disaster response propose the use of composite indicators as a quantitative tool, following the next steps: a general platform for the definition of the indicators, selection of the relevant indicators, comparability of the indicator through standardization and weighting, evaluation of consistency through validation and testing (Toseroni et al., 2016).

Enterprise Risk-Based Performance Management is an approach that facilitates maximizing value and competitive advantage to stakeholders, both in commercial and public sector organizations. There are strong parallels between performance management and risk management; the former is used to accomplish performance goals, and the second to maintain performance considering uncertainties. Risk reduction can be tracked through observable indicators, like injury frequency rates or the number of gas leakages or oil spills (Thekdi & Aven, 2016).

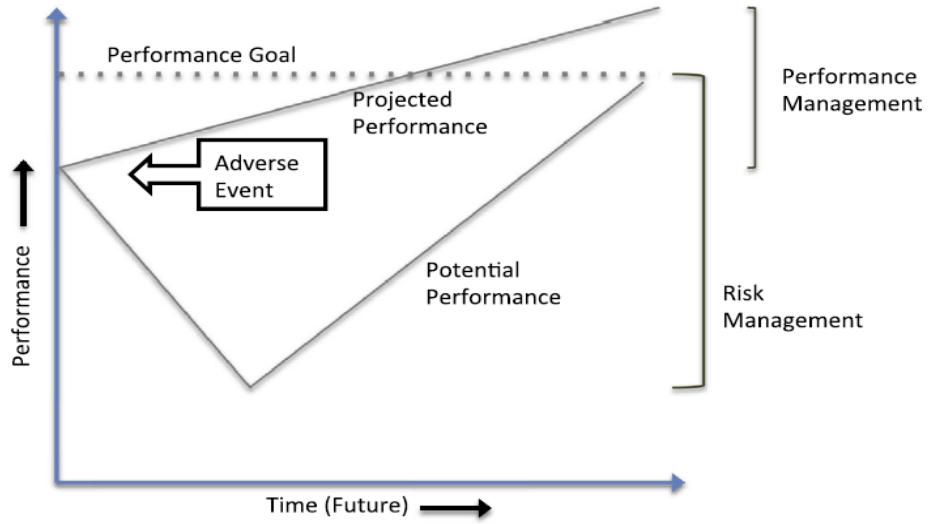
Performance management involving uncertainty and risk appetite to contribute to strategy execution set the basis for enterprise risk management (Cokins, 2009). The measurement of resilience based on organizational outcomes such as Operating Income to Sales, Key Performance Index (KPIs), Accidents Injury Rate, and Return on Equity (ROE), and energy return on investment constitute examples from the literature (Wang et al., 2019) (Ruiz-Martin et al., 2018). However, they lack assessment and empirical evidence.

The effects of climate change and the request to involve standardized ESG metrics offer an example of the need to integrate performance and risk management beyond safety. Limited research exists on this emerging challenge. The energy return on investment indicator, which allows the combination of energy return ratio with the financial return ratio applied to UOG in North America, is one of the few current proposals (Wang et al., 2019). Unfortunately, with the Canadian exception, the oil and gas industry has been slow to adopt standardized ESG metrics and goals.

Applying performance-risk metrics is particularly useful in low knowledge situations that offer growth opportunities, giving weight to vulnerabilities, resilience, and antifragility. A robust/resilient/antifragility behavior provides competitive advantages and superior outcomes for organizations with exposure to opportunity or loss (Thekdi & Aven, 2019).

Performance management focuses on the management of opportunity, and risk management emphasizes the lost opportunity. The future performance affected by events (stressors and opportunities) can lead to output above or below a reference level, expressing a planned value, a goal, or the current state. There are also uncertainties associated with these events' occurrence and the actual performance output (Thekdi & Aven, 2019). Figure 6 represents the different and complementary focus of risk management and risk performance in organizations.

Figure 6. Performance Management and Risk Management. Source: Thekdi and Aven, 2016.



Research for measuring organizational antifragility is limited. The dynamic system model of antifragility for CAS offers the ability to learn from experiences by forming new emergent structures previously unknown (Johnson & Gheorghe, 2013). The evaluation system builds on interest attributes to system stakeholders: strategies, policies, governance, structure, components, sub-systems, and processes. Unfortunately, the paper merely presented results for a hypothetical survey, and after that effort, only one framework to measure antifragility exists with identical limitations (Kennon et al., 2015).

2 THEORETICAL FRAMEWORK FOR ANTIFRAGILE ORGANIZATIONS

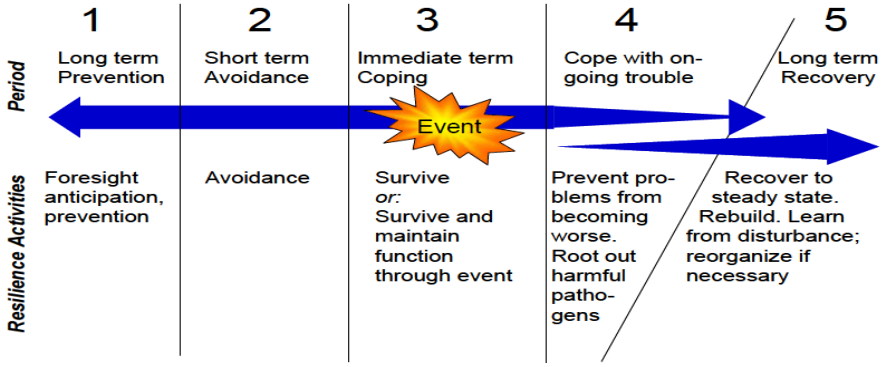
A social science theory can become an overarching framework for mixed methods research. It has several possibilities: a literature review, a conceptual model, or a theory that explains what the researcher seeks to find in a study (Creswell & Creswell, 2018).

A theoretical antifragility framework is required as a preliminary condition to identify and evaluate the findings from Medium-C and Small-C steps in this study. The organizational resilience framework literature review provided the foundations, which enhanced after involving the attributes from the most representative literature on antifragility, starting from Taleb's work. The challenge was to find relevant information knowing there are no definitions nor real firm cases documented. We selected updated grey literature to overcome this weakness, which provided enterprise cases and surveys, especially after the post-COVID-19 era.

2.1 Crisis Management Resilience Frameworks

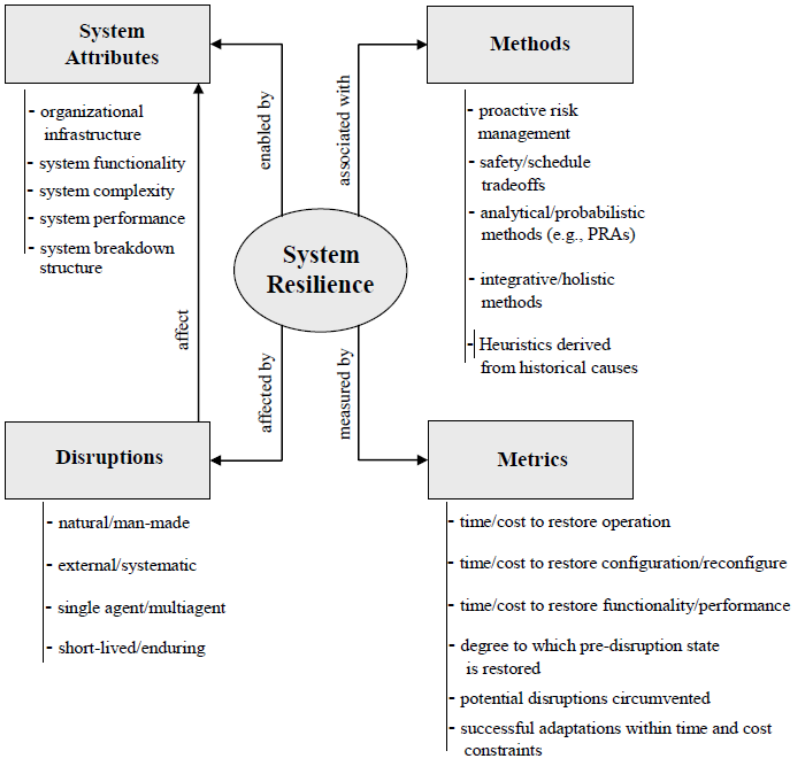
Crisis frameworks have evolved to reference the resilience organization conceptualization as a start point for the case study research analysis. (Sheard & Mostashari, 2009) presents the framework depicted in Figure 7 for system resilience with five aspects: periods, system types, events, resilience actions, and properties to preserve.

Figure 7. Framework for Resilience. Source: Sheard, S., 2009.



Contemporarily, (Jackson, 2007) provided a conceptual framework for understanding and analyzing disruptions based on lessons learned that could be employed to build resilient systems, showed in Figure 8. The framework comprises disruptions, system attributes, methods, and heuristics for developing resilient systems.

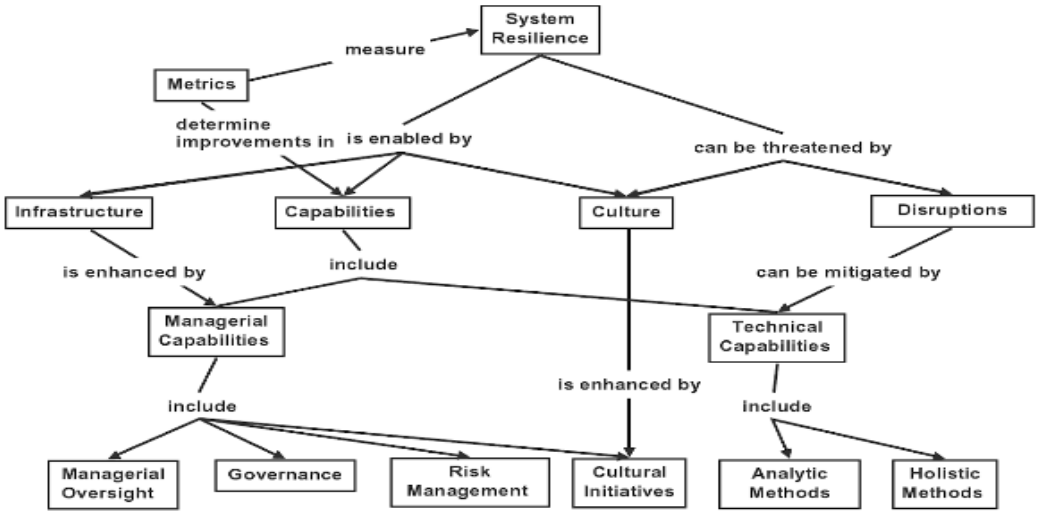
Figure 8. Conceptual Framework for Resilience Engineering. Source: Madni & Jackson, 2008.



The crisis management was improved with the Quality Management (QM) and the mindfulness concepts, as interpreted in the High-Reliability Organization (HRO) studies (Terje Aven & Krohn, 2014). The concept of mindfulness is about awareness and sensitivity for discerning the details essential for obtaining a high level of performance and avoiding catastrophes. It incorporates five characteristics: preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience, and deference to expertise. Aven and Krohn also accentuate the importance to incorporate the state of the art risk management and quality management in the framework to avoid significant accidents and losses.

(Jackson, 2007) offered a basic architecture for system resilience grouped into three categories: capabilities, culture, and infrastructure. Figure 8 shows an updated version released in his book in 2010. It is utilized in this study as a backbone to summarize the resilience framework state of the art complemented with the other analysis shown above.

Figure 9. The architecture of system resilience. Source: Jackson, S., 2010.



After crisis management, the resilience concept acquired relevance. There is copious literature that offers an ample selection of attributes, characteristics, and elements common to resilient organizations. After a detailed review of 110 works, the most relevant attributes are Building situation awareness, Managing an organization's vulnerabilities, Having resources, Improvisation capacity, Ability to anticipate events, Agility, Learning individuals, Resilient capacity, Collaboration, Flexibility, Robustness, and Redundancy (Ruiz-Martin et al., 2018).

2.2 Antifragile Theoretical Framework

Google Scholar statistics show an increasing number of articles incorporating the word “antifragility” Since 2015, 1,560 articles have appeared. 592 before 2015; 238 in 2016; 267 in 2017; 270 in 2018 and 304 during 2019; 287 until September 2020. When the search also incorporates the word “organization,” 894 results are obtained, 116 until September 2020. Literature focuses mostly on Engineering, Information Systems, Complex Adaptive Systems, and Psychology antifragility.

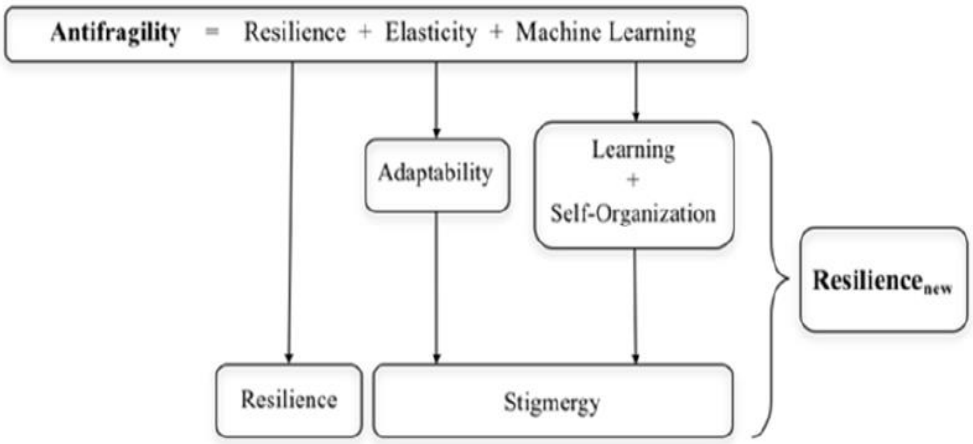
One relevant reason for the lack of studies incorporating antifragility in organizations is the absence of a formal definition. Taleb, in his seminal book Antifragile (N. Taleb, 2012), only highlighted some of the characteristics that such an organization may have:

- Ruled by the owners with an entrepreneurial mindset.
- Focused on their boundaries and strengths.
- Organization: small, redundant, not bureaucratic, collaborative, autonomous.
- Culture: flexible, agile, adaptable, transparent, respect for experience, and trust.
- Knowledge organization: trial and error, quality management, learning.
- Financially strong: low indebtedness, solvency, good performance.
- Eager to work under uncertainty and the stressors involved.
- Risk-taker with limited downside and complete optionality.
- Strong project execution by controlled steps.

Some additional attributes related to sustainability, such as self-regulated, circularity, and regenerative, are missing. Chapter 14, from the book The Big Pivot (Winston, 2017), offers a view of Sustainability attributes for antifragile organizations, which should consider the public expectations regarding the carbon-free economy from the future. We discuss Sustainability in more detail in Section 8.2.

The resilience framework was improved to reflect the need to cope with VUCA; thus, Adaptation, Learning, and Self-organization have been added to resilience to reflect the main antifragility attributes. Figure 10 shows the improved resilience results by mixing stigmergy and resilience (Passos et al., 2018).

Figure 10. The Evolution of Resilience. Source: Passos et al., 2018.

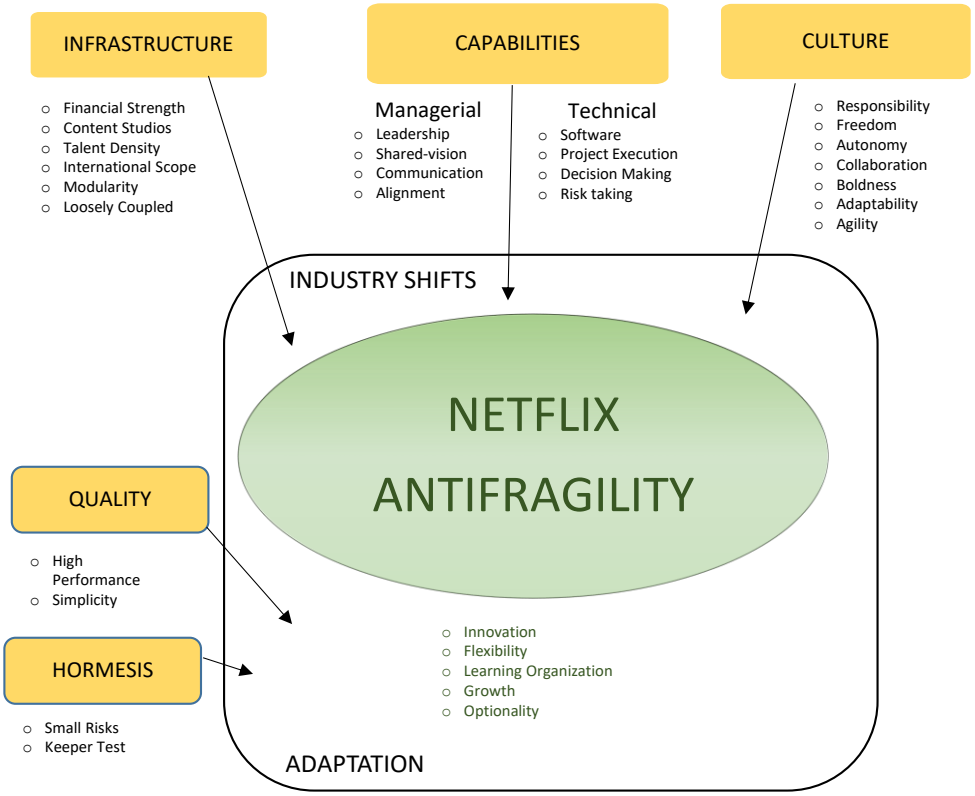


The Covid-19 pandemic evidenced the need for adaptation speed to cope with the uncertainties. A survey of 857 companies conducted by McKinsey & Company showed leaders asking for faster Decision-making mechanisms, improving Internal Communication and Collaboration, Innovation, Alignment, and increasing Technology use. Faster organizations outperformance their competitors and obtain better Performance, Profitability, Operational Resilience, Organizational Health, and Growth (De Smet, A., 2020).

Remarkably only one article portrays an actual case of an antifragile organization. It shows how Netflix's efforts to build resilience and how it can be improved by increasing the frequency and variety of failures and evolving the system to deal better with each newfound failure, thereby increasing antifragility. The main conclusion stresses that focusing on learning and fostering a blameless culture are essential organizational elements in creating proper feedback in the system, which becomes better the more times and ways it fails (Tseitlin, 2013).

The book No Rules Rules (Reed & Meyer, 2020), written by Netflix’s funder and CEO, shows the only company's history and culture we label as Antifragile nowadays. Figure 11 incorporates the conceptual framework presented above, together with McKinsey's survey results and the books described in this section. We named it after Netflix because most of the attributes are representative of this firm.

Figure 11. State of the art Organizational Resilience and Antifragility. Source: The authors.



According to the Netflix cult, some of the attributes in Figure 11 demand a further explanation, although the literature describes them adequately.

- Responsibility: Self-Organization, Self-awareness, Discipline, Ownership, Commitment, Self-motivation, and Accountability.
- Freedom: No controls, Not boss pleasing, and Autonomy.
- Boldness: High Performance, Stress for results, Improvement, and Execution.
- Learning Organization: Freedom, Innovation, Risk-taking, Trial and error, Non-Monotonicity, and Shared-vision.

Another example of an antifragile organization would be IDEO, the global design company founded in 1978. IDEO is famous for its ability to fastly design a great variety of innovative products through a diverse workforce of 700 employees in 9 locations worldwide. IDEO culture emphasizes attributes such as Execution, Collaboration, Optimism, No Rules, Leadership, Flexibility, Self-motivation, and Modularity. The distinctive characteristics of IDEO's culture are in Figure 11, which gives us the

confidence to test the theoretical antifragile framework for the case study selected companies.

Theory or theoretical propositions play a critical role in generalizing the lessons learned from the case study research (Yin, 2018, p.37). However, giving the lack of research on the antifragility concept, the theoretical framework from Figure 11 is the basis throughout this study for analytic generalization to shed empirical light on the main findings and contribute to developing or theoretical propositions, which could assume the form of a working hypothesis. It offers an initial theoretical framework to analyze and evaluate the antifragile unconventional oil and gas companies in North America and Latin America. The environment is different, with multiple possibilities for diversification and optionality in the first and country risk and lack of logistics and resources in the last.

3 UNCONVENTIONAL OIL AND GAS INDUSTRY

After the discussion presented in Section 3, we selected the unconventional oil and gas development sector from the oil and gas industry, in line with step one from the approach shown in Chapter 1. The firms selected for the mixed methods research are oil and gas organizations enduring and thriving to develop unconventional projects in Latin America and North America, where deep uncertainties exist, although at a different level. Addressing case identification from many potential cases can utilize formal and informal approaches (Gerring, 2017, p.71). In our case, we selected the top performers for the Medium-C and Small-C analysis.

The oil and gas industry routinely has to deal with high VUCA, megaproject execution, political, and exploratory risks. It faces additional challenges to obtaining the LTO, ESG goals setting and accomplishment, climate change, and energy diversification concerns. Additionally, firms are under constant pressure to reduce costs, generate positive returns and cash flows under distressing hydrocarbon prices. Managers and decision-makers possess engineering risk assessment capabilities but fail when dealing with the social factors associated with UOG (Torres et al., 2016).

The race to increase reserves and production and the adoption of new operational methods evidenced weaknesses in the regulation's unpreparedness, and from several companies to observe Generally Accepted Good Engineering Practice (GAGEP) (Castro-Alvarez, F., 2018). They fall short to respond appropriately to ambiguity, high uncertainty, and complexity. Several HSE risks impacted the early stages of UOG exploration and development in the US. Among the leading causes:

- The rapid increase of UOG activity.
- Implementation of new drilling and completion technologies.

- Overreliance on emerging small companies to seize prospective land and generate revenues.
- Fragile regulatory structures enforced by states to fill statutory gaps at the federal level.

Public opinion is contingent on the perception that UOG activity could trigger HSE, social and operational risks, relaxed regulation, and weak government control capabilities. Additionally, there are socio-economic impacts: boomtown effects, increased crime, prostitution and substance abuse, inflation and house prices, effects on well-being. Exist also an additional set of 'soft' impacts from UOG activity, which are more difficult for the oil and gas industry to mitigate: disrupting social attachment to places, change in relationships between individuals and their environment and institutions, undermining the transition to sustainable energy use (Cotton, Barkemeyer & Renzi, 2019).

Companies in North America do not have to address the challenges and uncertainties Latin American peers face. They solved most of the initial risks for North America and implemented new operational practices and cost reductions after the learning curve flattening. As a result, UOG firms focus on building scale through consolidation. Nevertheless, in addition to hydrocarbon price variations and operational constraints, there are several uncertainties to solve:

- Substantial variability among operators and inconsistency on how best to optimize.
- Inefficient use of capital: higher costs than promised.
- Shale production forecast overestimation.
- Doubts about the real possibility to generate profits at $50 a barrel.
- Continuous request for ESG goals implementation.
- Best practices are continually evolving with new technology and better methods.
- Difficulties in financing operations due to the reluctance from investors.

UOG exploration and development in Latin America have focused on Argentina, Chile, and Colombia. In the former, UOG activities began in 2011 in the Vaca Muerta formation, with technically recoverable resources on par with large US UOG plays. In contrast, Colombia enacted a temporary moratorium on UOG activities. However, several pilot tests to evaluate the environmental impact of UOG activities are underway. There is little progress to test the La Luna and Tablazo formations despite changes in a regulation

made in 2012, mainly due to public concerns regarding water sourcing and contamination. Elsewhere, Chile has made efforts to explore and develop UOG potential with promising results, and lack of government support has dampened exploration efforts in Mexico despite substantial UOG potential.

We describe the countries outside North America that could develop their UHR potential in chapter 5. Research studies list the different challenges that countries face to explore and develop UOG resources (Cooper et al., 2016) (Le, 2018) and (Castro-Alvarez, F., 2018). The main barriers identified are:

- Water sources and availability.
- Potential contamination of groundwater and surface water.
- Generation of greenhouse gases.
- Natural gas prices, primarily where uncompetitive market conditions exist.
- Opposition from society, in varying degrees.
- Uncertainty of resource estimation.
- Lack of local infrastructure, skills, and expertise.
- Policy and regulation.
- High capital requirements.
- Topographic and demographic conditions.
- Excluding landowners from any participation in oil and gas revenues.
- Weak government control capabilities.
- Lack of baseline and studies of potential health and environmental impact.

3.1 Extreme events

To evaluate the organizational resilience level after an extreme event, we selected the oil and gas industry during two extreme events that happened during 2014-2015 and 2019-2020. After several years of high hydrocarbon prices, the first event is the industry outbreak, which reached over $100/bbl in 2014 and decreased to under $40/bbl in 2016. Previous years were characterized by firms' orientation to growth to seize the opportunity through acquisitions, megaprojects, and exploratory commitments, fueled by abundant capital resources flow from the capital markets. As a result, there was cost inflation and a steady reduction in return to investment. The second event is the Covid-19 pandemic

Black Swan, which reduced hydrocarbon demand affecting commodity prices and investor's confidence.

Additional to the price outbreaks, the UOG firms suffered from treatment, disposal, and transportation constraints. A natural consequence of accelerated production growth is the lack of infrastructure to handle additional oil, natural gas, and water inflows. Consequently, production costs and price differential increased, leaving companies with lower cash flows and rising concerns on methane emissions and earthquakes in some regions, growing public protests because of the activity. The situation worsens in Canada and the Bakken basin due to permit delays to build new pipelines.

The impact of oil production bottlenecks was particularly strong in Canada. Companies had to limit growth in 2018-2019 and endure significant price discounts since authorities restricted production output. As a result, Apache (APA), Shell (RDS), Marathon (MRO), ConocoPhillips (COP), and Devon Energy (DVN) sold their assets and left the country during the evaluation period. Encana rebranded itself in 2019 to become Ovintiv (OVV) and changed its domicile to the US, transforming into a smaller fish in a bigger pond.

Oil and gas firms' market capitalization was severely impaired during both events. The S&P 500 composition's energy sector relevance by equity capitalization reduced from 26% during the energy crisis in the 1980s to 4% on December 31th, 2019. The US became the biggest oil producer globally, reaching energy security, but investors demanded capital discipline, free cash flow generation, and visible ESG commitment. Consequently, capital markets avoided public Initial Public Offerings, equity offerings, and debt issuances, the fuel that propelled growth during the golden years.

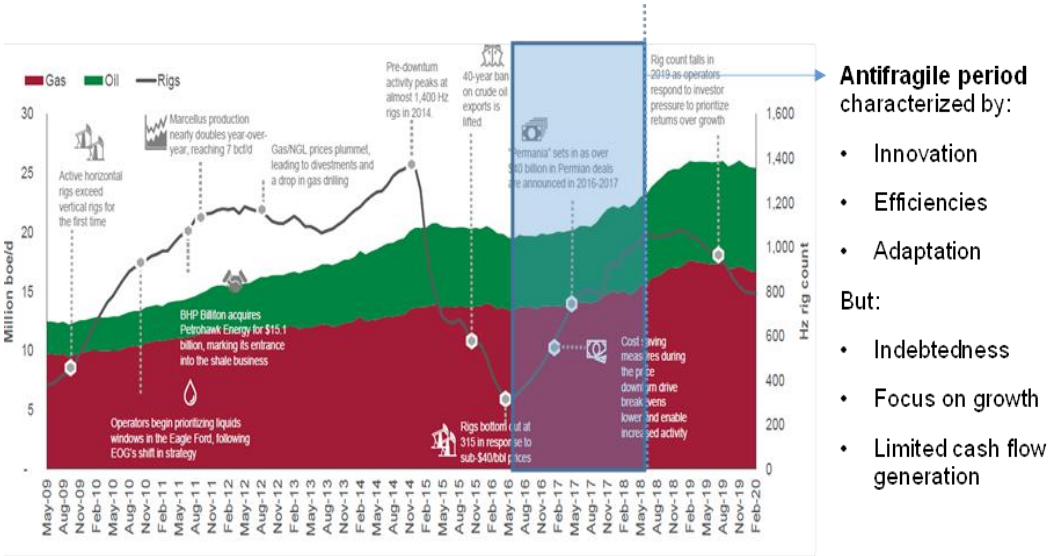
The hydrocarbon price collapse in 2014-2015 and 2019-2020 constitutes two disruptive events that allow measuring organizational resilience after five years of recovery time. Only in the US, oil and gas output increased 10 million equivalent barrels of oil per day, despite high costs, low returns, and growing funding needs. Companies had to innovate, adapt, and manage uncertainty to optimize production, reduce costs and risk exposure, and generate positive cash flows. The Fragile disappeared, the Robust and Resilient survived, and the Antifragile thrived.

3.2 Factory approach

UOG offers a remarkable example of industry and the firm's antifragility given those extreme events and challenges. The 2014-2015 oil price downturn forced companies to trigger innovations, efficiencies, and collaboration. They applied a trial and error approach for learning, collaboration, a shift towards a 'factory approach,' and, as a result, a significant increase in production output and cost reduction. Tight oil break-evens reduced by 45% from an average of $76/bbl in 2014 to a range of $37-47/bbl in 2019, thanks to structural efficiency gains applying the hydraulic fracturing technique. Figure 12 shows the increase in production output and, at the same time, the rig reduction at the Bakken and Permian basins after the price collapse.

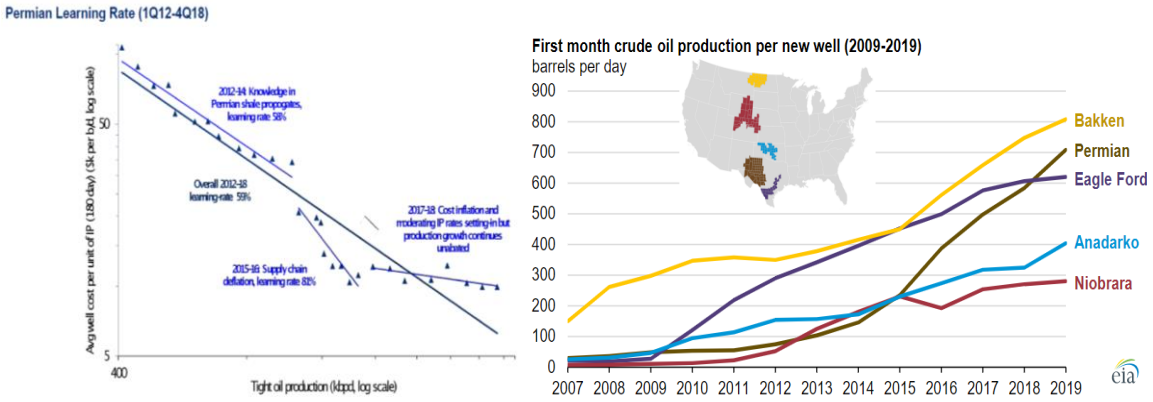
Production and development costs are a proxy for measuring innovation and technology adoption, but it is necessary to isolate factors like economies of scale and cost inflation. UOG and production costs increased during 2011-2014. However, after 2015 they reduced steadily with a learning curve of 3.989% for a sample of 30 US companies due to technology development and productivity gains (Kim & Lee, 2017). Similarly, companies transfer UOG exploitation know-how and best practices to other countries. Unit capital costs reduced in Argentina by 36% during 2011-2014 and in a range of 9-40%, and China during 2013-2017, through joint ventures composed of the US companies, and NOCs or local firms (Cr & Hafner, 2018).

Figure 12. Oil industry antifragility response to 2014-2015 oil price downturn. Source: Wood McKenzie, 2020.



High uncertainty, trial and error, poor project execution, flexibility, collaboration to increase output, and simultaneously costs reduction after an extreme event, among others, constitute a relevant set of factors representing organizational antifragility behavior, as listed in Section 1.2. However, several firms exhibited an inadequate response to the 2014-2015 price collapse. As a result, they filed for bankruptcy, were acquired, or required substantial capital inflows to survive. The Covid-19 pandemic offered an additional opportunity to evolve after changing the 'production growth' focus for 'returning cash' to increasingly disillusioned investors. Figure 13 depicts how the learning curve for well cost and oil production per well increased after 2015 from 59 to 81%.

Figure 13. The learning curve and well productivity by region. Source: Citibank Research, 2019; EIA, 2020.



QM, Just-In-Time (JIT), Supply Chain Management (SCM), and Lean Manufacturing, among other techniques, have been applied for oil and gas companies involved in UOG development, altogether commonly named as the 'factory approach.' QM used to be almost inexistent for conventional oil and gas operations, characterized by its uniqueness that impaired the possibilities for standardization and the resulting cost control.

4 CRITICAL FACTORS FOR COUNTRY UNCONVENTIONAL HYDROCARBON DEVELOPMENT

Worldwide, many countries struggle to exploit their UHR to ensure energy security sustainably, but few have been successful. Regulators and decision-makers have to elucidate the critical factors required to attract International IOCs. They underpin NOCs by bringing the practice, capital, and technology required to spur innovation and develop those abundant resources in sustainable and profitable ways.

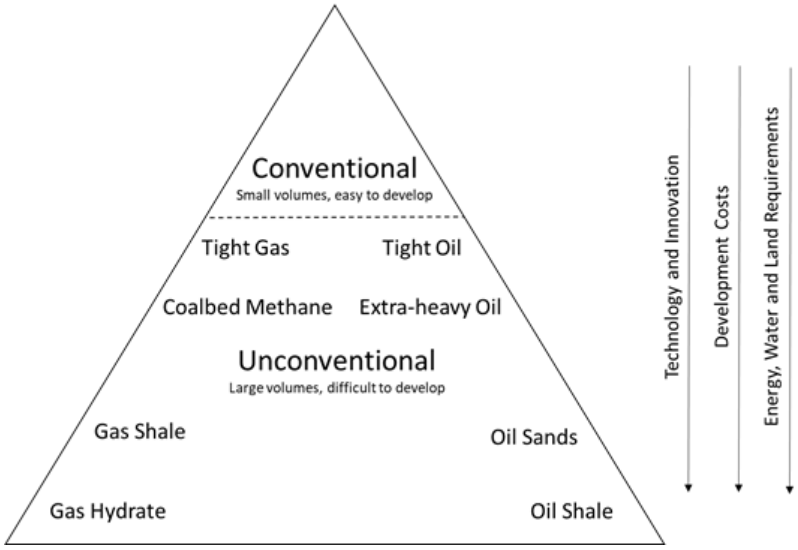
We observe the UHR commercial development from 60 countries and identify the most relevant critical factors for the 22 most active. We select the most representative eight critical factors to evaluate and grade them in the 22 countries with the most UHR development activity. To integrate the results, utilize the proposed Unconventional Development Index (UDI), which allows modeling the countries evaluated for ranking, benchmarking, and forecasting purposes. It also offers the possibility of simulating variations in the critical factors for any studied nation and evaluating its behavior and opportunities to achieve commercial success.

4.1 Global Unconventional Hydrocarbon Resources

Hydrocarbon composition is equal to conventional and unconventional reservoirs. There are seven types of UHR: tight oil, tight gas, extra-heavy oil, coal bed methane (CBM), shale gas, oil sands (natural bitumen or tar sands), oil shale, and gas hydrates (methane hydrates). Figure 14 depicts the different hydrocarbon reservoirs, considering the size of the deposits, the cost, environmental impact, and technology level required for development (Holdith, 2006). UHR is located worldwide in 476 formations and 363 oil and gas basins in 60 countries. The recoverable oil resources in the world account for

30,855x10^{8} billion barrels (Bbl) and 6,900x10^{12} trillion cubic feet (Tcf) of natural gas, excluding gas hydrates (Wang et al., 2016) (Tong et al., 2018).

Figure 14. Hydrocarbon reservoir classification (Holdith, 2006), adapted by the authors.



There is a wide UHR development range among the 60 analyzed countries, with less than 22% reaching commercial development. The shale group (tight oil, tight gas, or gas shale) reduces to 11% of the 46 countries with potential according to the Energy Information Administration (EIA) World Shale Resource Assessments (EIA, 2015). Table 1 evaluates and groups the countries in six categories, considering UHR type and current development status. The categories for the analyzed countries are defined as follows:

1. No interest: having either high conventional production, water stress, or challenging political environment to generate the minimum conditions for UOG development.
2. Bans, Moratoria, or License rejection: applied to hydraulic fracturing and shale exploration and development activities. License rejection involves those countries where the time to grand licensees for exploitation is too long in response to public sensitivity, leading to the affected projects' suspension.
3. Lack of LTO: public opposition is too strong, restraining exploration activities.
4. Exploration: evaluating UHR potential through geological studies, surveys, pilot tests, and appraisal before funding development project approval. It can have three stages: (1) preliminary studies; (2) exploration activity (seismic, well drilling, pilot test); and (3) failure. There could be small quantities of hydrocarbon production during exploration

activity. Failure occurs after several exploratory dry wells, and as a consequence, IOCs abandon any UHR activity.

5. Uncommercial Development: there is UHR exploitation solely by NOCs. IOCs lose interest because of difficulties in exploiting, commercialize hydrocarbons and obtain minimum financial returns.
6. Commercial Development: UHR exploitation with participation from IOCs and NOCs. It divides into Innovators and Successful followers.

Table 1. Countries with significant UHR potential current development status. Source: the authors.

Category	Sub Category	Shale	CBM	Extra-Heavy Oil	Oil Shale	Gas Hydrates
No interest		Brazil, Lybia, Chad, Iran, Irak, Egypt, Pakistan, Tunisia, Qatar, Kazakhstan, Australia, Russia, Venezuela	Russia, China	Russia, China, Saudi Arabia	Uzbekistan, Republic of Congo	US, Russia, Canada
Bans, moratoria or license rejection		France, Bulgaria, Netherlands, Ireland, Denmark, Belgium, Italy, Czech Republic, Germany, Scotland, Mexico, UK		Canada		
Lack LTO		Algeria, South Africa, Romania				
Exploration	Preliminary studies	Ukraine, Hungary, Spain, New Zeland, Peru, Morocco, Jordan, Kuwait, Indonesia	Vietnam, Botswana; Indonesia		Ukranie; US, Australia; Russia, UK	Norway
	Exploration activity	Colombia, United Arab Emirates, Bahrain	Colombia		Mongolia, Morocco	Japan, China
	Exploration failure	Poland, India				
Uncommercial Development		China, Saudi Arabia, Russia	China			
Commercial Development	Innovators	US, Canada	US, Canada, Australia	US, Canada	Estonia	
	Successful Followers	Argentina, Turkey, Oman, Chile		Venezuela	Jordan, China, Israel, Germany, Brazil	

Countries with the ability to attract IOCs to work together with their NOCs possess the minimum critical factors required for UHR commercial development. IOCs bring the best practices, technology, and capital needed to implement the trial and error approach to spur innovation, reduce cost, optimize productivity, and avoid environmental damage. If successful, the best performers could be Antifragile because they can operate in uncertain environments, triggering options to grow and reduce costs while complying with local regulation and ESG requirements.

4.2 Factor definition

We select eight critical factors and grouped them into three different categories:

1. Government Support
2. Exploration
3. Commercial Development.

Government support is essential for executing exploration activities. We utilize UDI to compute the critical factor weight. However, it is not part of the essential factors since countries like Turkey have developed their shale potential despite its comparatively small UHR potential.

Table 2. Critical Factors and weights required for UHR development. Source: the authors.

Critical Factors	Weight
1. Government Support	**20%**
Size of potential Resources (Tight Oil) - bn bbl	
Size of potential Resources (Shale Gas) - tcf	
Political environment	5%
Conventional and Other Competition	15%
2. Exploration	**55%**
Geology	20%
Land/access Operability & Water Stress	10%
Enabling fiscal regime	10%
Public Opinion (LTO)	15%
3. Commercial Development	**25%**
Oil & Gas Infrastructure	15%
Innovation	10%
	100%

Table 2 shows the selected factors and their weights. We obtain the grading for the different factors from actual result observations from grey literature and specialized oil and gas industry reports. Political environment and Innovation factors scoring from the ranking and pillar metrics within the GII-19 index.

Factor weights obtained from UDI generate a compound average for the analyzed nations. Having equal weights allows country standardization and ranking. However, actual weights may differ for a particular country according to its internal priorities, strengths, and weaknesses. The most studied cases compare the US and China actual shale gas development efforts, where factor weight differences are significant (Yang et al., 2017).

4.3 Unconventional Development Index

The UDI allowed ranking the 22 studied countries, according to their grading for the eight selected critical factors, utilizing the most reliable information regarding their efforts for

UHR exploration and development. Table 3 depicts the factor grading and the resulting UDI scores for each country.

Table 3. Unconventional Development Index (UDI) ranking for the 22 analyzed countries. Source: the authors.

	US	Canada	Argentina	Australia	Oman	Chile	Turkey	Jordan	China	Russia	UK	Saudi Arabia	UAE	Venezuela	Bahrain	Colombia	Poland	Mexico	Romania	Algeria	South Africa	India
General Information																						
Size of potential Resources (Tight Oil) - Bb	78	9	27	16	48	2,3	5	6,8	32	103	-	-	205	167,3	13,7	7,4	2	13	50,7	6	-	
Size of potential Resources (Shale Gas) - Tcf	623	573	802	429	10,5	48,5	24,7	0,1	1115	285	26 - 130	600	22,6	13,4	81	54,7	145	545	0,3	707	390	96
Companies																						
Onshore Producing IOCs	68	59	22	46	1	1	9	0	22	22	17	1	0	19	0	14	0	9	3	6	0	14
UOGD Operator IOCs	37	13	8	17	2	1	1	0	0	0	1	0	0	13	0	3	0	0	0	0	0	0
NOCs	0	0	1	0	1	1	1	1	4	2	0	1	1	1	1	1	3	1	1	1	1	1
Total	37	13	9	17	3	2	2	1	4	2	1	1	1	14	1	4	3	1	1	1	1	1
Critical Factors																						
1. Government Support																						
Political environment	5	5	1	5	3	3	1	1	3	1	5	1	5	1	1	1	3	1	1	1	1	1
Conventional and Other Competition	5	4	5	5	5	5	5	5	5	3	5	5	3	3	5	3	5	3	5	3	5	3
2. Exploration																						
Geology	5	5	5	5	5	5	5	5	3	5	3	3	3	5	3	3	1	5	3	5	3	1
Land/access, Operability & Water Stress	5	5	5	5	5	3	3	5	1	5	3	3	3	5	1	5	3	3	3	1	1	1
Enabling fiscal regime	5	5	3	3	3	5	5	3	3	1	5	1	1	1	3	3	3	3	3	1	3	3
Public Opinion (LTO)	3	3	5	3	3	5	3	5	5	5	1	5	3	3	3	3	5	1	1	1	1	3
3. Commercial Development																						
Oil & Gas Infrastructure	5	5	3	3	5	1	3	1	3	3	3	3	5	3	5	3	1	3	1	3	1	3
Innovation	5	3	3	3	1	3	1	1	5	3	5	3	3	1	1	3	3	1	1	1	1	1
Unconventional Development Index	**4,70**	**4,35**	**4,10**	**4,00**	**4,00**	**3,90**	**3,60**	**3,60**	**3,60**	**3,60**	**3,50**	**3,30**	**3,20**	**3,10**	**3,10**	**3,10**	**2,90**	**2,80**	**2,40**	**2,40**	**2,20**	**2,10**

The highest UDI scores reflect the innovator's commercial development situation. The lowest grading is for the countries with the most severe difficulties in exploring UHR. The index score could differ slightly according to the resource type or another relevant factor. In Argentina's case, where natural gas infrastructure is at total capacity, the UDI score is 3.8, whereas oil is 4.1, modifying the Oil & Gas Infrastructure grade from 3 to 5. Another case is Venezuela, scoring 3.1 for extra-heavy oil and 2.8 for shale, by adjusting the grading for Conventional and Other Competition factor from 3 to 1.

4.4 Innovation

Several countries worldwide struggle to develop their UHR potential to ensure energy security and enhance their Gross Domestic Product (GDP). The few nations that have successfully developed it suggest that possessing the resource is not the only condition to exploit it effectively. We identify the critical factors required for UOG development and model them to demonstrate that it is mandatory to fulfill most of them to develop UHR commercially.

Commercial Development Innovators, the US (shale, CMB), Canada (extra-heavy oil), and Australia (CMB) have the top UDI scores thanks to their world-class infrastructure, political environment, and innovation, among other critical factors. The cases of Estonia (Shale Oil) and Japan (Gas Hydrates) are not part of this study, given their lower span.

GII-19 score for all of them is in the top tier, the US (3th), Japan (15th), Canada (17th), Australia (22th), and Estonia (24th), suggesting the importance of country innovation in the early stages of UHR exploitation (Yang et al., 2017). They started activities in a less demanding ESG environment, and further research and innovation will be required to comply with the current sustainability requirements.

The cases of China, Saudi Arabia, and Russia denote that despite the abundant UHR and the strong government and financial efforts to develop their resources, the lack of innovation is crucial to hinder UOG development. China and Saudi Arabia have attracted oil service companies to bring the latest technology but missed a favorable environment to bring IOCs to lead innovation and overcome their inherent difficulties.

By contrast, Argentina, Oman, and Turkey, categorized as Successful Followers, have effectively attracted IOCs to spur the innovation required to reduce costs and optimize production output. They are not experiencing environmental and social demands, mainly because the shale oil fields are located close to oil and gas infrastructure in remote desertic areas with water availability. When reviewing the GII-19 innovation ranking, they place 53th (Argentina), 86th (Oman), and 72th (Turkey), showing that innovation skills did not come up with the countries but with the IOCs.

The cases of Venezuela and Canada reflect how the key factors evolve. Two decades ago, the former successfully attracted IOCs to jointly with the NOC, PDVSA developed its extra-heavy oil resources. However, the weaker political environment and the fiscal regime have scared away IOCs, and the fields are struggling to operate. The second offers a less extreme case. The difficulties experienced in building the necessary infrastructure to respond to the increasing production due to environmental and social concerns have impaired IOC’s financial returns and equity value. As a result, IOCs like Apache Corp (APA), Devon Energy (DVN), and Encana fled the country in the last four (4) years after selling their Canadian assets.

Additionally to Oman, UAE, Jordan, Saudi Arabia, and Bahrain are making efforts to exploit UHR by attracting IOCs, reducing surface and subsurface risks, and improving fiscal regime conditions, reflected in a range of UDI scores 3.1 to 4.0. These countries exploit their advantages of land availability except for Jordan, which focuses on shale oil

development. They take advantage of existing oil and gas infrastructure, abundant UHR resources, government commitment, and lack of social issues. They also reduce exploratory uncertainty by investing in exploration and mimic the example of Saudi Arabia to bring seawater to the oil and gas fields and minimize GHG emissions. Together with the tax flexibility and strong NOCs, they attract the required IOC investment for UHR development.

In contrast to other industries, political environment weight is not high because IOCs are accustomed to operating in harsh regions. Country risk is an issue only in situations of political or economic unrest. Such is Ukraine's case, where despite the UHR potential and government support, IOCs left the country after the Russian invasion and have not returned ever since.

On the other hand, the lack of LTO and government support have stopped the initial exploration efforts from UK, Mexico, Romania, Algeria, and South Africa, among other countries where shale development is banned. Social and government support are critical issues for UOG development.

UDI score reflects UHR exploration and development degree of success. It positively correlates with the number of IOCs in each country (correlation coefficient=0.62 and R2=0.39), reflecting the relevance of IOCs presence in a country to have successful UOG exploitation. Nevertheless, causality is difficult to establish. Although IOCs may spur investment, innovation, and development, reverse causality is also possible: after successful UOG development, IOCs arrive. To overcome this issue, we consider the relationship between existing onshore IOC companies and UDI instead of IOCs devoted to UOG development.

The variation in the observations of UDI and IOCs existence obeys the confluence of the identified factors. E.g., UK, Colombia, and Venezuela, with more than 10 IOCs and a UDI score lower than 3.6, have social acceptance concerns the former's first and political issues. On the other side, nations like Chile, Oman, Turkey, and Jordan are developing UHR thanks to the absence of geological, infrastructure, and logistic challenges that do not demand vital innovation and capital, making IOCs presence less needed.

IOCs bring capital, technology, and good practices to promote innovation via trial and error and generate the virtuous cycle required to obtain green production and financial returns through operation optimization. Governments can facilitate the process through UHR support, surface and subsurface risk reduction, fiscal regime improvement, and ESG practice promotion.

UOGD in Chile and Argentina reflects the first step toward UDI technological maturity. The ENAP-Sipetrol (Chile's NOC) and Tecpetrol (Argentinian Techint's subsidiary) ability to learn from the IOC's operators in Argentina and the United States demonstrates that the technology is not proprietary. However, it is becoming a standard industry practice. Unfortunately, we did not find a way to isolate each specific country's innovation, and capital needs to compare them across the different nations involved to evaluate it most precisely.

In addition to Chile and Estonia's lower-scope situations, there are no cases where NOCs have developed UHR independently. In light of such evidence, we have good reasons to expect that Follower Countries should attract IOCs to develop UHR. IOCs should bring capital, technology, and good practices to promote innovation via trial and error and generate the virtuous cycle required to obtain green production and financial returns through operation optimization. Governments can facilitate the process through UHR support, surface and subsurface risk reduction, fiscal regime improvement, and ESG practice promotion.

5 ANTIFRAGILE OIL AND GAS COMPANIES

Measure the organizational resilience level after an extreme event is a challenge we address in this chapter. We propose several standard metrics for the oil and gas industry, which may extend to other industries. As a result, it is possible to identify Antifragile UOG companies for different countries.

5.1 Metric definition

Enterprise Risk-Based Performance Management emphasizes the utilization of customary metrics to evaluate resilient behavior. Appendix B summarizes the most accepted oil and gas industry and the UOG subsector indicators grouped into seven categories. It is far from having industry ESG metrics consensus, so we include the most sounding proposals to date.

There is a deep cliff among investors and operators regarding the proper metrics for enterprise value creation. On the corporate finance side, there are four cornerstones for value (Koller, 2011, p.4):

1. Generate cash flows at rates of return, exceeding the cost of capital.
2. Generate cash flows, not by rearranging investors' claims on those cash flows.
3. Changes in the stock market's expectations drive prices as much as its actual performance.
4. The value of a business depends on who is managing it and what strategy they pursue.

On the operational side, the value metrics orientation toward:

1. Oil and gas reserves growth.
2. Oil and gas production growth.
3. Operational and development cost.

The organizational resilience level for the firms should incorporate both views. However, since operational output depends on price and market fluctuations, in the medium term, reflected in the five years in this study, financial data is more reliable and reflects the firm's ability to cope with extreme events. Nevertheless, the selected indicators shall reflect firms' objectives to satisfy both investors' requirements and stakeholders' intense scrutiny. As a result, we incorporated four metric categories:

1. Financial
2. Operational
3. ESG
4. Value

Table 4. Selected Resilience Indicators. Source: the authors.

Resilience Indicators			
Category	Fragile	Robust -Resilient	Antifragile
Financial	Altman's Z score		
	Net Debt/EBITDA	EBITDA	Z-Score Recovery
	Liquidity ratios	Gross Margin	EBITDA growth
Operational	Breakeven price		
	Production		Production growth
	Injury rate		
ESG	GHG Emissions		
	Energy use		
	Freshwater use		
	Land impact		
Value	Cash Flow Generation		
	Market Capitalization		
	ROIC / ROCE		
	TSR		

We evaluate several metrics to identify the most suitable for resilience measurement under the MMRO. Table 4 shows the selected indicators. The shadowed metrics are more valuable to rank and classify the resilience level.

The primary metric defined to measure resilience in this study is the multivariate discriminant Altman's Z-Score model. During the last five decades, the model's power has been demonstrated in predicting bankruptcy and financial distress, performing and adapting well to the international context, compared to other hazard models (Altman et al., 2017). We found that despite the data to develop the original model from 1946-1965 for manufacturing firms, the results are good enough to avoid using different coefficients developed over other companies. There are few references for the application of Altman's Z-Score to energy firms. The case analysis of Suzlon Energy Ltd for the 2014-2018 period offers a close resembling the present study (Mehtha, 2020).

The utilization of Altman's Z-Score has first described in 2006 as a performance and strategic assessment tool. The metric proved its strength to yield insight into enterprise profitability and growth over more traditional ones (Calandro, 2007). The model application to measure resilience under extreme events has limited use. Nevertheless, a case demonstrates the correlation between the Z-Score and employees' creative involvement and its contribution to organizational resilience (Brezuleanu, 2015).

Following the antifragility definition described in chapter 2, the resilience indicator may utilize an additional metric reflecting growth, such as EBITDA and oil and gas production increase. The first includes the price realizations and the ability to transport and commercialize hydrocarbons in better conditions due to strategic decisions through the value chain. The former is more straightforward, especially for projects and subsidiaries, but ignores the operational flexibility required when oil prices are low, or any disruption exists.

An additional factor considered is the cash flow generation. There was significant funding to the sector for UOG growth. Firms raised about $22 billion from equity and debt financing in 2018, less than half the total in 2016, and almost one-third of what they obtained in 2012. It was a fundamental reason for several companies in financial distress conditions to avoid filing for bankruptcy despite the low hydrocarbon prices. Only 27% of

the US Independent oil peer-group, including asset sales, hedging, and divestitures, had positive cash flows in 3Q 2018 (Rystad Energy, 2019). Hence, an additional requirement for antifragility is Cash Flow from Financing (CFFF) for the 2015-2019 period to be positive. Investors and the public are requesting more actions to reduce gas flaring, water and land use, carbon benchmarking, climate risks, and ESG goals. It will be necessary to incorporate an ESG metric to involve the firm's sustainability commitment in the medium term. The most prevalent indicator is GHG Scope 1 and 2 emissions intensity. Section 9.2 shows GHG measurements for Canadian companies adjusting 2018 corporate ESG reported values according to asset bases (Ho, 2020, pp. 12–14).

GHG emission may contribute to Resilience and Performance management in the medium term as more companies commit to reporting and independent organizations standardize measurements. Methane emissions are estimated to be 25 times more potent as a warming agent and critical for meeting Paris agreements. Canada committed to reducing methane emissions by 40% of 2012 levels by 2025. The Fugitive Emission Management Program Effectiveness Assessment started in 2019, becoming a clean-tech leader in methane and CO2 emissions reduction.

Similarly, the DuPont Bradley Curve may be utilized to measure safety resilience behavior. DuPont's firm classification as Reactive, Dependent, Independent and Interdependent resemble the Fragile, Robust, Resilient, and Antifragile MMRO classification.

5.2 Resilience Measurement

Strategies evolved in response to stakeholder needs. Growth versus cash flow generation is the main drive in the requirements from the market to the companies. During 2009-2019 firms lure investors with practices like leveraged and stock acquisitions and organic growth after aggressive land acquisition. Organizations focused on efficiencies and cost control after the price crisis from 2014-2015. When excess cash was available, companies distributed it to shareholders through share buybacks and dividends.

By contrast, after 2019, companies started to respond to investors' pressure to prioritize returns, debt reduction, and ESG goals. As a result, strategies focused on cash flow

generation at the expense of growth. To achieve this industry goal, firms utilized practices such as hedging, capital expenditure optimization, debt refinancing and payment, no leveraged acquisitions, dividend and production curtailment, and midstream project cancellation. Excess cash would distribute as variable dividends depending on the current oil price and financial results.

We collect and evaluate financial and operational data from 77 firms and their subsidiaries, focusing the study on those with market capitalization superior to $1 billion by December 31th, 2019. We include several representative independent companies with a lower market capitalization in Canada (12) and the US (12) to enrich the analysis. Table 5 shows Peer Groups and the number of companies selected.

To evaluate Fragile companies, we review 213 bankruptcy filings in the US and 18 in Canada for 2015-2020, from Haynes and Boone, Oil Patch Bankruptcy Monitor. We select the 47 filings with total secured and unsecured debt higher than $1 billion, finding reliable financial information for 23 companies. Additionally, we analyze the 45 most relevant oil and gas asset and firm transactions in North America during 2019-2020. The sources of financial and operational data were Gurufocus, FracFocus, and Wood Mack databases.

Table 5. Peer Group companies and main relevant financial attributes. Source: the authors.

Peer Groups	Quantity (N=77)	5-year CAGR (%)					
		Market Cap	ROIC	Gross Margin	CFFF/MC	EBITDA	Z-Score
Canadian Integrated	4	4.1%	6.6%	11.9%	10.6%	-7.4%	-15.9%
Canadian Seniors (> $1bn MC)	8	-5.8%	7.4%	33.0%	2.5%	-4.5%	-74.7%
Canadian Juniors (<$1bn MC)	12	-10.3%	6.4%	34.4%	6.8%	-14.8%	-98.9%
Global Majors	7	3.5%	2.5%	11.7%	27.2%	5.4%	-18.1%
International Independents	5	-1.2%	5.9%	20.6%	12.3%	-2.3%	-42.9%

Table 5. Peer Group companies and main relevant financial attributes. Source: the authors (Continued).

US Independents (>US 1B MC)	26	1.6%	6.1%	23.3%	-5.7%	9.2%	-35.4%
US Independents (<US 1B MV)	12	-10.5%	8.9%	30.6%	-101.2%	3.1%	138.1%
Latin American NOCs	3	25.2%	5.1%	3.0%	109.8%	10.9%	-5.8%
p-value		0.004	0.005	0.003	0.001	0.006	
Correlation Coefficient		0.964	-0.714	-0.840	0.792	0.213	
Determination Coefficient		0.929	0.510	0.706	0.627	0.046	

UOG activity in Latin America is focused mainly on Argentina and Chile, with some exploratory efforts in Colombia. With few exceptions, companies execute projects through joint ventures between NOCs and Global majors. Independents focus in North America, diversifying activities across several basins, the US, and Canada. Since financial information is not available for branches, the analysis centers exclusively on their operational outcomes. ENAP-Sipetrol Chiles' NOC is performing development activities alone in legacy assets taking advantage of the Argentinean experience.

It is not simple to evidence resilience response to extreme events in the short term since almost all companies curtail production and reduce costs. These measures could reflect either operational flexibility or financial distress, making it challenging to evaluate them. Moreover, some companies behave conservatively while others aggressively in response to the collapse hydrocarbon price crisis.

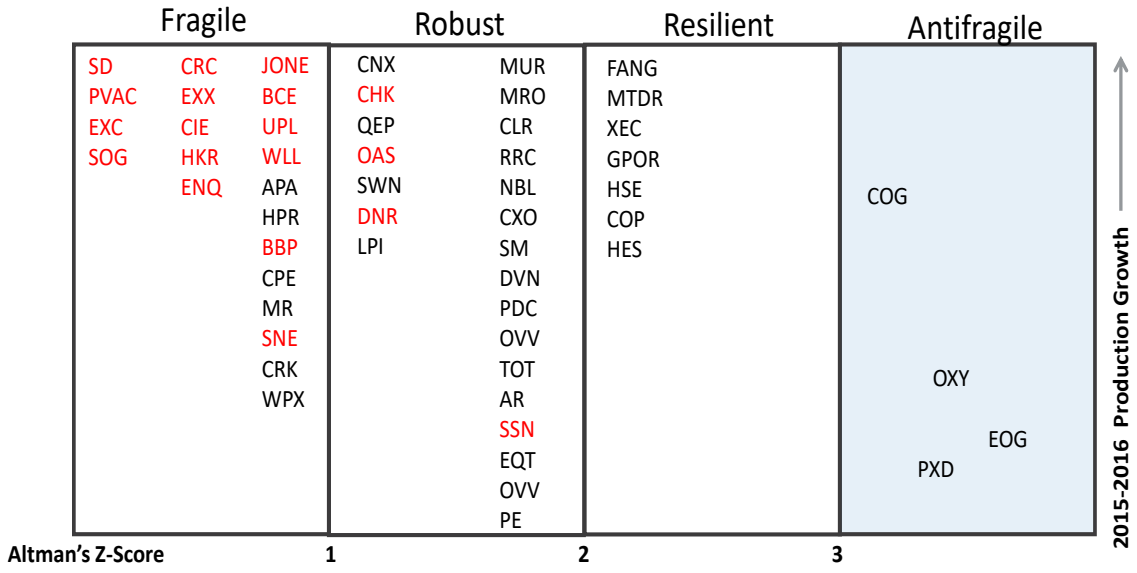
Given the differences in size, scope, geographic span, diversification, and product type for the companies within the defined peer groups in this study, it is not reasonable and statistically significant to individually contrast the 77 firms analyzed. Instead, we do compare the averages of some selected financial five-year median values. Table 5 summarizes the average results for the peer groups' p-values and coefficients. There is a

strong correlation between Z-Score and market capitalization variation, suggesting that Z-Score is a good proxy for evaluating value generation perceived by stockholders in the medium term. Additionally, Return on Invested Capital (ROIC) and Gross Margin increase for all the peer groups, reflecting the efficiency gains. It contrasts with Z-Score reduction, especially for smaller companies, due to an overall deterioration in financial strength resulting from indebtedness to fuel growth, extreme events, and high operational costs.

5.2.1 The United States

Figure 15 shows the resilience classification for Global Majors and the US Independents before the first extreme event. Altman's Z-Score in 2014 allows us to rank the companies according to their resilience level. One year of production growth for the period 2015-2016 fits the criteria for antifragility. Firms in red are those filing for bankruptcy during the five years of July-2015 to the June-2020 period.

Figure 15. Resilience level classification for UOG Global and Independent US companies in 2014. Source: the authors.



The resilience level scale from Figures 15 and 16 follows Table 5 financial and operational metric evolution for the five-year evaluation period. Antifragile firms have a Z-Score higher than 3.0 in 2014. They exhibit a recovery time, Z-Score equal to or higher than the initial value, between one to three years, with (Occidental Petroleum) OXY's

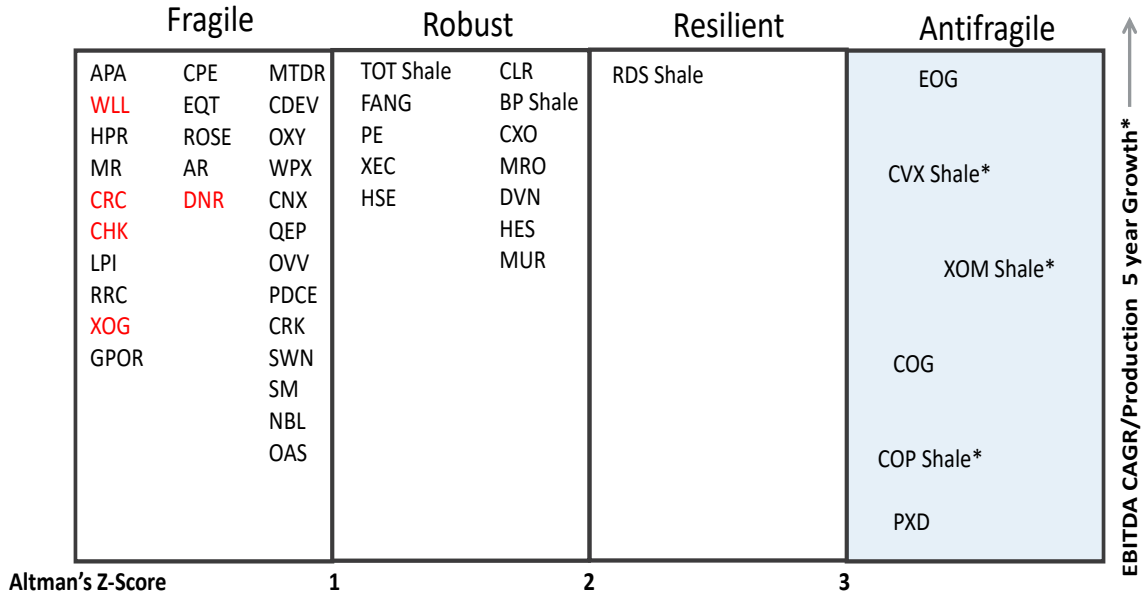
exemption after the leveraged Anadarko (APC) acquisition last 2019. Similarly, they showed a positive five-year CFFF and EBITDA CAGR growth. ExxonMobil (XOM) and Chevron (CVX) denoted production growth limitations worldwide, but together with EOG Resources (EOG), experienced a sharp UOG production increase during the period. By contrast, Resilient and Robust companies with Z-Score higher than 1.0 and lower than 3.0 did not recover despite consistent output growth, reflecting a lower 5-year ROIC increase rate associated with efficiency gains than Antifragile ones. In Section 8.1, we discuss the main strategies tactics followed by antifragile companies.

71% of firms (in red on Figure 15) holding a Z-Score lower than 1.0 within the analyzed sample filed for Chapter 11 bankruptcy in one to five years, and three with a Z-Score higher than 1.0 did it after 2015. These results are not conclusive since they depend not only on the firms' internal strengths but also on the possibility of obtaining external financing through asset sales, equity raising, and indebtedness.

There is high significance in the fact that less than six months before the Covid-19 pandemic happened, three companies with market capitalization higher to $1 billion by the end of 2018 filed for bankruptcy in 2Q-2020. The Chesapeake Energy (CHK) case is the most astonishing since it shaped the US's UOG. CHK's business model was oriented to grow at all costs and lease aggressively, hence being an innovator and first mover in several basins. The downside was the borrowing in excess. The early bet for gas and natural gas liquids development instead of oil, which worked for Cabot Oil & Gas (COG), did not for CHK due to its higher costs, lower well productivity, senior debt interest obligations, and reduced gas prices.

Clear differentiation between Robust and Resilient companies is difficult to establish. The scale of 2.0 helps separate the two groups to reflect the MMRO model, which is convenience rather than a specific metric variation. Figure 16 depicts the firm's resilience ranking following the same criteria. ConocoPhillips (COP) and Global Major's Antifragile behavior reflects the US UOG asset portfolio's relevance and the diversification possibilities through the downstream infrastructure that characterize oil and gas integrated companies.

Figure 16. Resilience level classification for UOG Global and Independent US companies in 2019. Source: the authors.



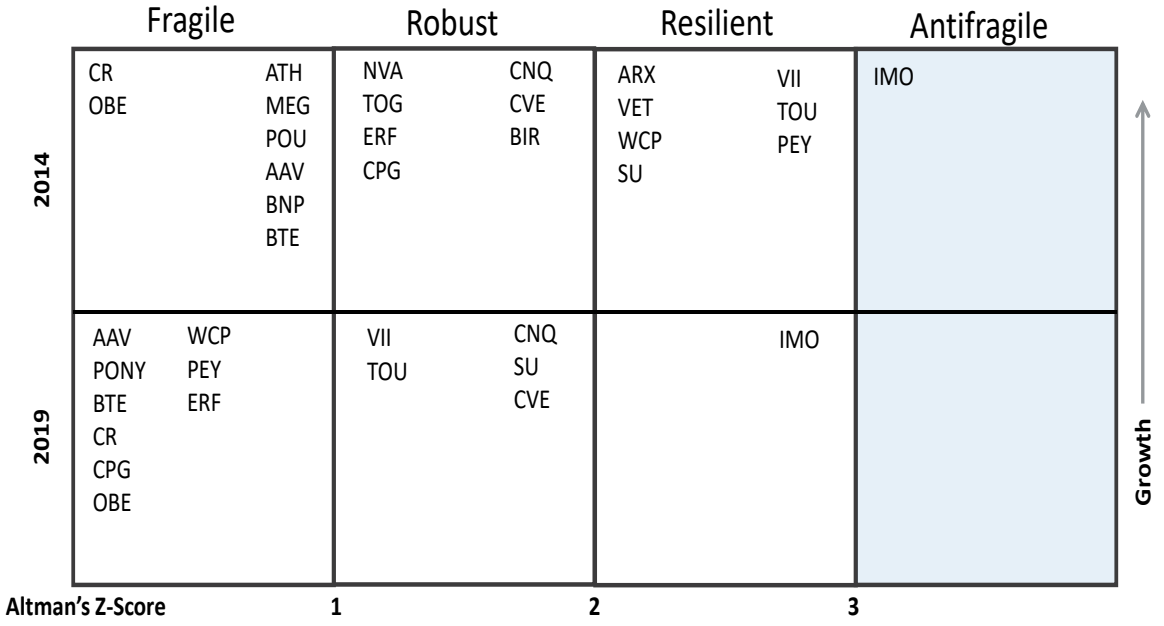
5.2.2. Canada

The financial stress that characterizes companies in the oil and gas industry is evident in Figure 17. The Canadian sector's difficulties are portrayed in Section 4.1 and reflected in Z-Score reduction for most firms. The companies with the lowest Z-Score discount are Imperial Oil (IMO) and Canadian Natural Resources (CNQ), which belong to the Canadian Integrated group, showing the relevance of vertical integration along upstream, midstream, and downstream chain value segments. It offers companies the possibility to control the whole process, diversify risks, reduce costs, and improve efficiencies.

CNQ's ability to increase five-year ROIC by 9.5% and Gross Margin by 27.7% for the evaluation period reflects its ability to keep EBITDA CAGR and debt constant, despite the sharp decrease in hydrocarbon prices.

Diversification is a critical factor for Canadian firms to survive. Five-year EBITDA CAGR increase for Baytex Energy (BTE) 80.6%, Vermilion Energy (VET) 15.6%, Enerplus Corp (ERF), 10.9%, thanks to their assets in the US, which helped them to invest in the areas with a better margin.

Figure 17. Resilience level classification for Integrated and Independent Canadian firms. Source: the authors.

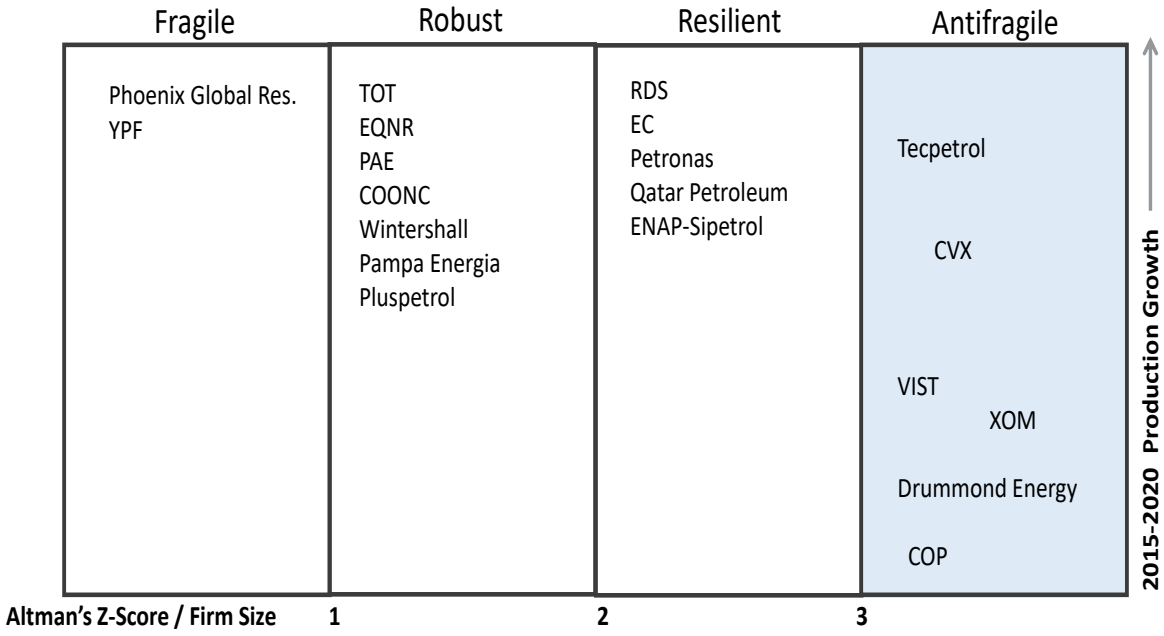


5.2.3. Latin America

UOG exploitation in Latin America implies additional challenges compared to North America. Firms have to deal with country risk, supply chain constraints, reservoir uncertainties, lack of oil service companies, and public opinion misconceptions. Global parent companies transfer financial strength to their subsidiaries and operational experience to local companies through joint ventures.

Given the lack of financial disclosed information available, we defined subsidiaries' organizational resilience level through a combination of North American firms' financial data and local production growth. We utilized firm size as a proxy when financial information to compute Z-score was unavailable; thus, Figure 18 results are descriptive rather than exhaustive. XOM and COP have UOG activities in both Argentina and Colombia.

Figure 18. Resilience level classification for UOG Latin American firms. The authors.



The firm's antifragile behavior in Argentina follows the availability to increase production faster than the rivals to take advantage of natural gas and oil prices and have market access before, given the infrastructure constraints. In Colombia, it reflects the ability to perform pilot tests delivering production before regulation issues arose. Another useful operational indicator for subsidiaries is the breakeven price, which offers a straightforward way to capture financial strength and the upside associated with additional oil and gas reserves. Further research is required to test and improve the MMRO measurement proposal for international contexts.

6 CASE STUDY RESULTS AND ANALYSIS FROM ARGENTINA

6.1 Argentina UOG Landscape

Despite the significant increase in oil and gas production from UOG reservoirs in North America, Argentina is the only country able to replicate it with a similar level of success. Other countries' challenges in obtaining comparable results are environmental concerns, lack of technical expertise, unavailability of water and land, elevated costs, and uncertainties in the production potential (Bravo & Hernandez, 2020a).

Argentina's case is self-explanatory: during 2012, the NOC Yacimientos Petrolíferos Fiscales (YPF) invested US$ 920 million to drill 67 vertical wells at the Vaca Muerta basin, which catalyzed the signature of joint-venture agreements with Chevron Corporation (CVX), DowDuPont, and Petronas during 2013-2015 to complete the exploration phase (YPF, 2016). Loma Campana field development after 2015, in partnership with CVX, brought standardization, scale, and optimization to reduce costs and increase well productivity. Since 2016, horizontal drilling and the factory model are standard practices, following the US and Canada trends. By 2018 over 30 IOCs and local companies hold acreage in the area, which required US$1.9 billion to reach full development (Hayum, 2018). YPF holds a majority position with a strong pipeline of shale projects and a partnership strategy to gain financial strength and technology to optimize further. Today, the business mantra is to have profitable UOG exploitation after the Covid-19 pandemic.

On the other side, aboveground risks weigh heavily in Argentina. Undeveloped transportation infrastructure, macroeconomic, political, and market risks are difficult to stand for IOCs. The partnership with YPF helps them handle them, which constitutes a convenient win-win situation. The most relevant uncertainties that Latin American firms face to explore and develop unconventional oil and gas resources are (Guzman, 2018):

- Changes in regulatory and economic incentives.
- Public acceptance.
- Weak Government control capabilities.
- Lack of studies of potential health and environmental impact.
- The value proposition for all the stakeholders involved.
- Hydrocarbon potential and extensive development feasibility.
- Oil and gas prices and markets.
- Cost reduction achievement.
- Technical evolution to maximize productivity per well.
- Complex project execution.

From an operational perspective, Argentina has benefited from studying and applying lessons learned from US UOG developments; however, aboveground risks weigh heavily. Political risk is particularly relevant, with price controls, inflation, devaluation, and macroeconomic instability directly affecting oil and gas revenues. Social and economic concerns encompass oil rent distribution, income disparities, boom-town challenges, and indigenous people's effects. The relation of energy price uncertainty and country stability to understand how UOG development affects Argentina's geopolitical condition is critical. Uncertainties faced by organizations exploring and developing UHR are substantially different between North America and Latin America. Environmental risk in Argentina differs according to local regulations. While Neuquén made improvements to prevailing regulation, the other two oil-producing provinces of Salta and Santa Cruz have not (Zerda et al., 2017).

UOG development in Chile and Argentina reflects the first step toward UDI technological maturity. The ENAP-Sipetrol (Chile's NOC) and Tecpetrol (Argentinian Techint's subsidiary) ability to learn from the IOC's operators in Argentina and the US demonstrates that the technology is not proprietary. However, it is becoming a standard industry practice. In the case of Argentina, where UOG happens in an area far from towns, the factors and weights are Geology (20%), Commerciality (15%), Oil Field Service Capacity (15%), Financial Structure (10%), E&P Landscape (10%), Regulatory Landscape (10%), Infrastructure (10%) and Development Constraints (10%) (IHS Markit, 2019).

After the one decade of successful UOG exploitation, there are several challenges to overcome to take full advantage of the proven UHR potential:

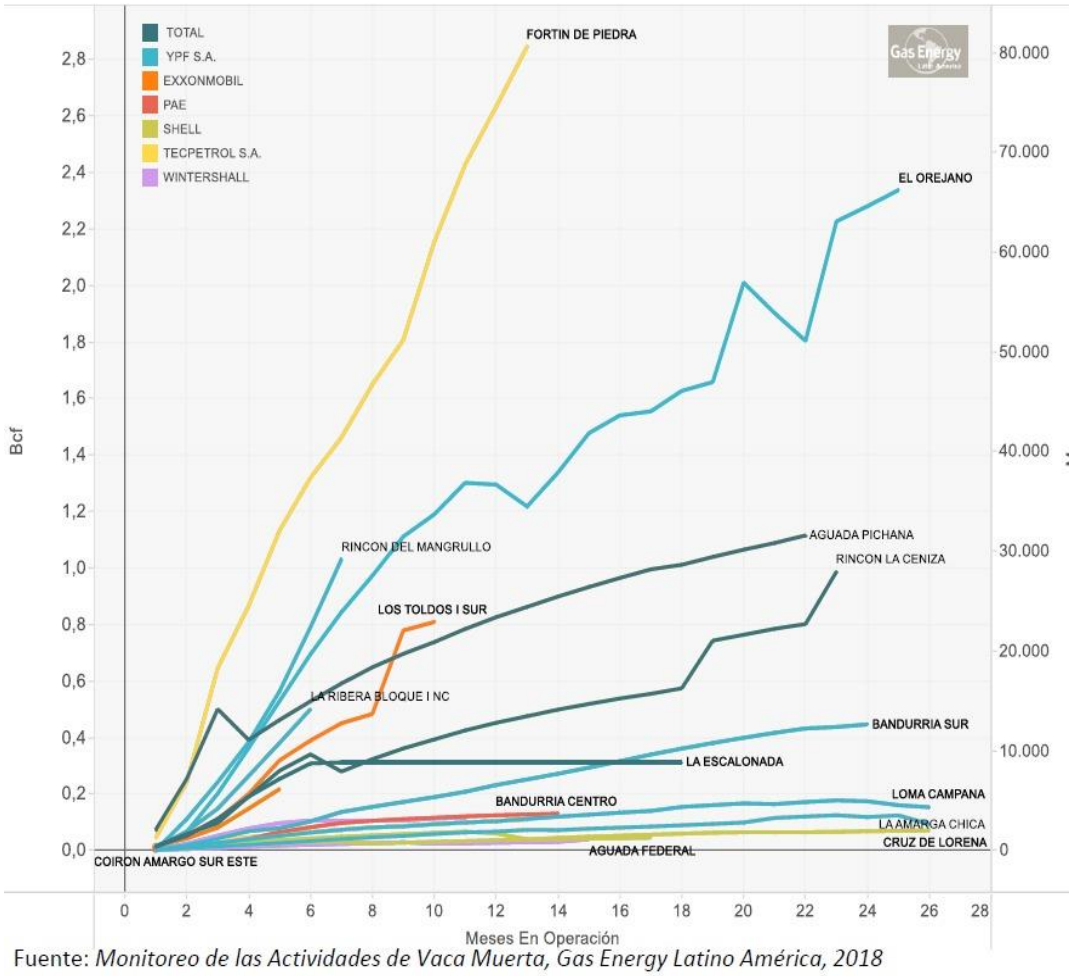
- Data availability and sharing to foster collaboration and innovation among companies.
- Improve data gathering, integrated field planning, and factory mode practices.
- Massively move from pilots to factory mode.
- Continue capturing cost efficiencies.
- Transportation and midstream investments to avoid current bottlenecks.
- Develop a Liquefied Natural Gas export facility.
- Macroeconomic and hydrocarbon price environment improvements.

6.2 Tecpetrol

In the Introduction, we discuss the criteria to select Antifragile companies for the case study analysis. In Latin America, the sector is developing unconventional resources, and it is not possible to establish benchmarking financial performance indicators yet. Then, to define the best performers, the capability to execute successful projects considering time, cost, and production increase is the indicator we utilize to identify antifragile companies. Figure 19 shows the best performers based on project and output deliverability.

Vaca Muerta Basin expects to reach almost 900,000 boe/d (280,000 b/d of oil and condensate and 95 mmcm/d of gas) by 2024, which will require US$4 billion of investment per year. Shale gas production will quadruple in five years, driven by the incentivized price and high well productivity. 3-year lead time is typical for the pilot phase. Given the increasing number of pilots, this time may shorten as the play is de-risked. YPF and the Provincial Oil Company (POC) Gas y Petróleo del Neuquén (GyP) are present in almost all awarded contracts, as seen in Figure 20. YPF’s partners gain access to local expertise, the most central acreage, and critical infrastructure, benefit from the NOC’s experience, service sector access, and the cost reductions achieved as a first-mover. Partnerships with YPF are strategic for majors, while smaller operators choose licensing rounds, and those with more cash and tight timelines will seek direct negotiations (Wood Mackenzie, 2019b).

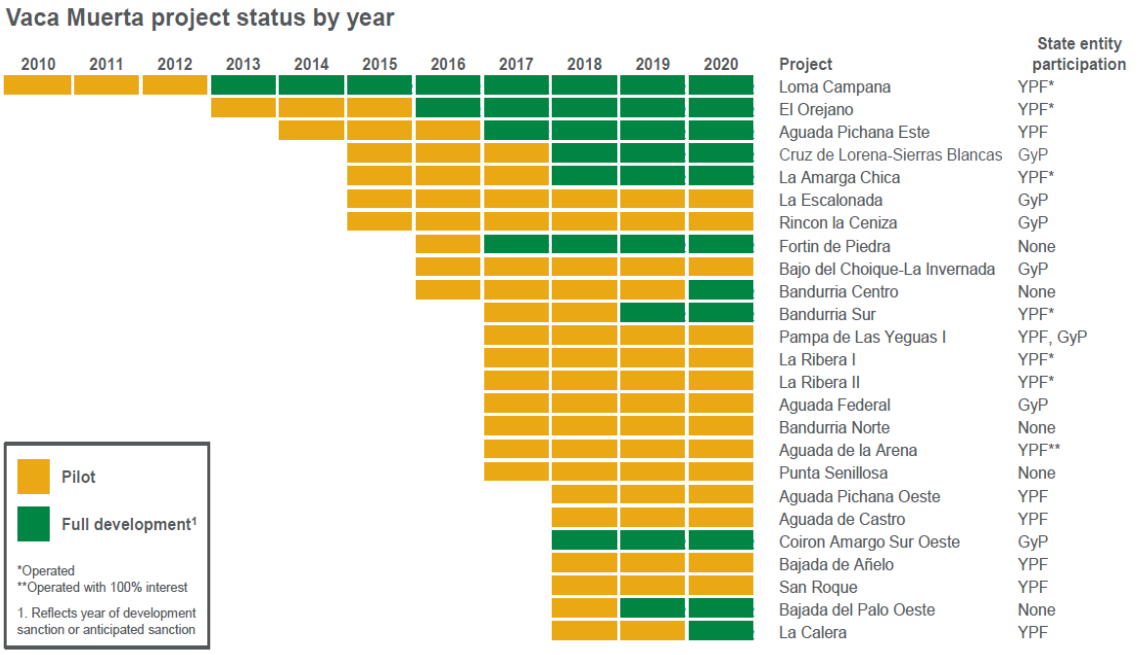
Figure 19. Best unconventional development project performers in Argentina. Source: Gas Energy Latino América. 2018.



Fuente: *Monitoreo de las Actividades de Vaca Muerta, Gas Energy Latino América, 2018*

Tecpetrol's Fortin de Piedra is the lead project without any state participation, the first to do it in only one year of pilot execution. Fortin de Piedra was the first natural gas project to move ahead with aggressive development to take advantage of high prices, leaving similar projects behind (Wood Mackenzie, 2019a).

Figure 20. Project sorted by state entity participation and execution lead time. Source: Wood Makenzie.



The companies from North America that are developing projects in the Vaca Muerta basin and the investment commitment year are:

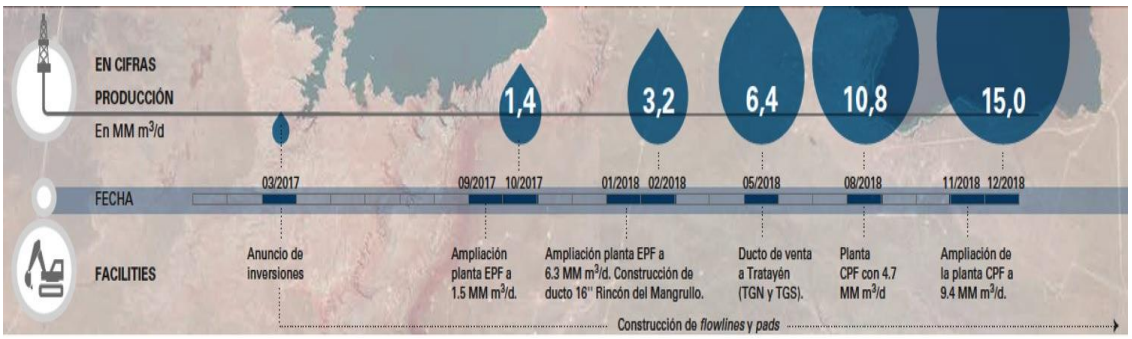
- Chevron (CVX): Loma Campana (2013), Loma del Molle Norte (2017).
- ExxonMobil-XTO (XOM): Bajo del Choique, La Invernada (2015), Los Toldos I Sur (2017), Sierra Chata (2017).
- Total (TOT): Rincón La Ceniza, La Escalonada (2014), Aguada Pichana (2017), Aguada de Castro (2017).
- Shell (RDS): Sierras Blancas and Cruz de Lorena (2015), Bajada de Añelo (2017).

Different factors, such as block placement near existing facilities, contractor availability, type of fluid, and investment commitments, explain developing projects' speed. Nevertheless, Tecpetrol's performance to develop a natural gas project in only 18 months is remarkable for the overall oil and gas industry.

Fortin de Piedra project committed $2.3 billion of investment starting in May 2017 to 2019 to execute 150 wells with six drilling and two completion rigs, 245 kilometers of pipeline,

and a Central Natural Gas Plant to process and produce 15 million of m3/day of natural gas. Figure 21 shows the project evolution within time.

Figure 21. Fortin de Piedra project evolution. Source: Tecpetrol, II Foro Internacional de Proyectos, 2019.



Some of the critical project accomplishments are:

1. Hired 4,500 employees. 1,000 Tecpetrol and 3,500 contractors.
2. At the development sanction in March 2017, seven wells drilled and three more in the remainder of 2017.
3. Tecpetrol brought 53 wells onstream in 2018.
4. The first horizontal wells in 2016 cost US$15.3 million to drill and complete, and that average cost decreased to US$12.5 million in 2018.
5. By November 2018, achieved gas production was 13 Mm3/day (467 Mcfd), and at the year-end, the goal of 15 Mm3/day.
6. It completed the aggressive plan within cost (1.5% overrun), time, and production and safety targets.
7. Oil reserves 451 Mboe, 52 Mbo crude oil, and 399 Mboe (2,223.4 Bcf) equivalent gas.

Mcfd: Million cubic feet per day.

Mm3: Million cubic meters.

Mbo(e): Million of oil (equivalent).

Bcf: Billion cubic feet.

6.3 Extreme Crisis Response

Tecpetrol participates in the Argentine Resolution 46 program, in which the government offered unconventional operators up to $7.50/mcf for incremental production above a baseline. Resolution 419 of 2017 specified that only incremental production above a baseline could receive the incentivized US$7.50/cf price (Resolution 46 price). They defined the baseline as average production from July 2016 to June 2017, 7.7 Mcfd for Fortin de Piedra. Companies had initially submitted minimum volumes for Plan Gas back in 2016.

In early 2019, the government surprisingly announced that production above the operator's initial target is not eligible for the subsidy. Subsidies capped at the operator's initial target level, 300 Mcfd for Fortin de Piedra. Production above this level is included in the 'base' production below and will receive the market price. The government pays the difference between the market and the subsidized price directly to all sales gas operators. The government has made these payments with significant delays up to one year.

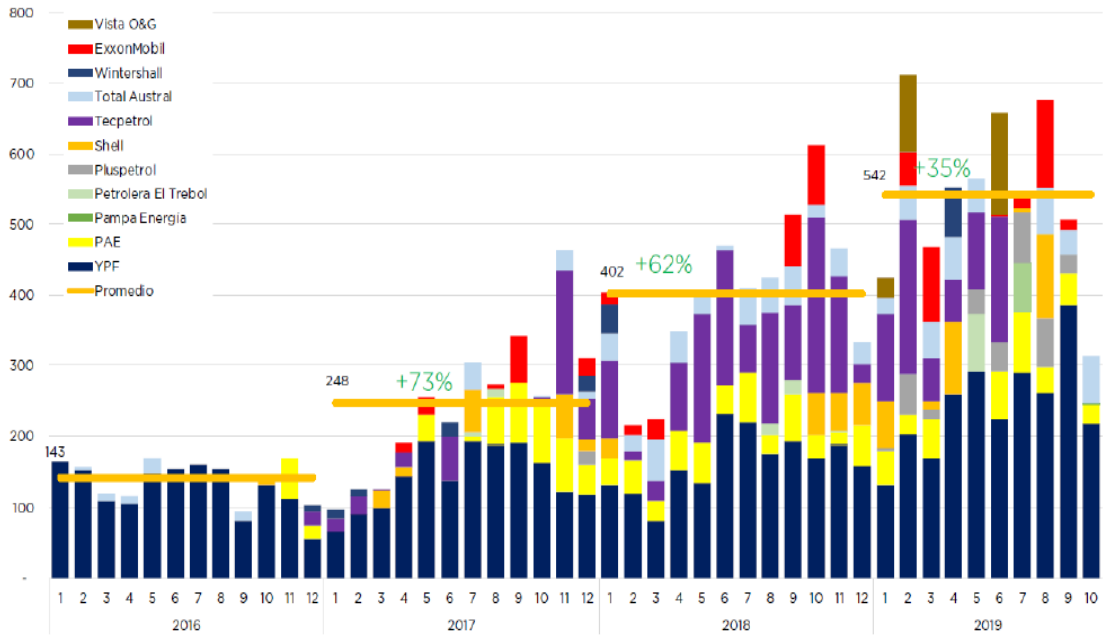
Tecpetrol's project faced material risk from a change in volumes about the field when the announcement produced near 2.0x the volumes presented back then. Fortin de Piedra production over 300 mmcfd will not receive the contracted subsidy, which has critical financial implications (Wood Mackenzie, 2019c).

As a result, Tecpetrol slowed drilling from 6 to one rig and stopped the project plans to build a gas pipeline from Vaca Muerta to Buenos Aires by Techint, the parent of Tecpetrol's company. Figure 22 shows the number of pumping steps by month, the best indicator of activity per company. The indicator fell to zero for Tecpetrol as a response to natural gas price changes.

Additional to the demand reduction, the Covid-19 pandemic and the storage constraints affected the Neuquen Basin activity. Vaca Muerta registered 0 pumping fractures on May, 25 in June, and 44 in July 2020. The oil fields and companies with the resilient capability to restore production first were Bajada del Palo Oeste (Vista Oil & Gas), Loma Campana (YPF-Chevron), Bajo del Choique-La Invernada (ExxonMobil), and Fortin de Piedra (Tecpetrol). Companies able to export Medanito oil production during June (Petronas,

Vista Oil & Gas, Tecpetrol, Pampa Energia, and ExxonMobil) could restore production faster and lower crude spreads versus Brent (Wood Mackenzie, 2020b).

Figure 22. Tecpetrol's Expand and Abandon options. Source: Luciano Fucello, Energy Ministry, 2019.



6.4 Antifragile Attributes Grading

We utilize the Antigragility Theoretical Framework from Section 2.2 (Figure 11) to portray the Attributes observed during the field trip, grey literature review, and interviews with Tecpetrol's workers and service providers. We modify it to include the specific additional characteristics found. The case study results, together with the similar one performed to Drummond and presented in the next chapter, allow us to build the Antifragility Framework discussed in Section 8.3.

We grade the Attributes qualitatively utilizing green, yellow, and red colors to reflect the observed capabilities and resources available. We describe the main reasons for each Attribute score in the Comments column for each one. The results are outstanding since they reflect a higher performance than the peers in similar operational conditions in the same basin. We made the discussion of the findings in Chapter 8.

Table 6. Tecpetrol's Resilience and Antifragility Attributes. Source: the authors.

	Infrastructure			Comments
	Parent			Techint Group – Private, 59.000 employees
		Financial Strenght		Z=0.7 as December 31st, 2019
		People		Top performers; Project: 4.500 employees
		Supply Chain		Tenaris: pipelines; Ternium: steel; Techint Engineering & Construction; Tenova: solutions; Tecpetrol: Oil, Gas & Transport; Humanitas: health; Exiros: supply
		Redundancy		Not evidenced
		Vertical Integration		An upstream company with access to midstream facilities
		Portfolio		6 Blocks in Vaca Muerta, 282 acres. No UOG outside Argentina.
	Local			
		Modularity		PAD Management teams
	Capabilities			
	Managerial			
Resilience		Leadership		Strong project leadership; Not role leadership models evidenced
		Governance		4 Levels: Strategic Techinp Group (Standards), Petrotec (Planning), Operational (Drilling, Project, Production) - Pad Man and Pad Management (6 PADs)
		Adaptive Risk Management		Project executed by steps with updates after new information from wells and market

		Communication	All Tecpetrol aligned under the same goal: 500 MMSC in November 2018
	Technical		
		Risk Assessment	Avoid well interference and well hits; Keep well integrity
		Decision Making	Optimize well spacing and design to maximize production and recovery. Operational decisions to improve performance
		Project Execution	2.300 CAPEX Budget; -1.5% Cost Execution, 8 months before plan.
		Best Practices & Standards	Best practices from Technit; Tank development instead of staggered; Taylor Method
	Culture		
		Responsibility	Daily Planning-Execution review
		Autonomy	Autonomous PAD Management teams
		Collaboration	Full integration among Techint subsidiaries and the different Tecpetrol's teams
		Agility	Main goal: 500 MMSCFD in November/18 versus July/19 plan; Fast-follower
Antifragility	Adaptation	Innovation	Drilling design modified from Slim to Robust because of well integrity problems
		Learning Organization	Transfer best practices from parent and improvements among the teams; Field visits to the US: Pioneer (PXD)
		Flexibility	Private Company. From 7 to 1 rig in operation according to project and market needs
	Growth	Optionality	Expand, Abandon, Execution by steps

	Diversification	Change from gas to oil among Vaca Muerta blocks
	Sustainability	Seismicity complains in Sauzal Bonito; 2 dead workers May 2019; Water from the river; Venting; No ESG goals
Quality	High Performance	Factory model before peers; 1-year pilot execution versus 3-years peers
	Efficiencies	35% cost/time reduction from initial to final well completions; PAD construction: 230 to 165 days, Drilling time: 42 to 30 days; Completion -30%
Hormesis	Small Risks (Trial and Error)	Constant design, planning, execution test to improve efficiency and gain productivity
	Stressors	Pre & Post Job Review: control against improving goals

7 CASE STUDY RESULTS AND ANALYSIS FROM COLOMBIA

7.1 Colombia UOG Landscape

UOG is controversial, raising strong opposition due to sustainability issues associated with exploitation, such that environmental concerns tend to overshadow economic benefits. Some people have already concluded that any effort to regulate UOG activity would be useless, and a harmful impact is unavoidable. With all the uncertainties that come into play and solid public opposition in most cases, why take the risk? The question follows the 'precautionary principle' notion, which expresses that it is best to wait until all the uncertainties of a given activity are fully understood. Colombia and Mexico are examples of this situation. As a result, no significant advances have been made to test La Luna formation in Colombia, despite changes in regulation last made in 2012, mainly due to strong public opposition to water contamination fears.

Colombia has a significant potential for the seven types of UHR found. However, there is high volume uncertainty due to a lack of information (Vargas C.A., 2012). Declining conventional hydrocarbon exports are relevant for GDP and energy security and the main reasons to become another country pursuing UOG exploitation. Incorporating the results and experiences from other nations reflected in the UDI allows us to evaluate and forecast the country's real possibilities to obtain UHR commercial development and adjust the critical factors.

The hydrocarbon production in Colombia has begun to decline since its 2015 peak due to a mix of lower oil and gas investment, a little exploration, a lack of relevant discoveries, and the maturity of the producing oil fields. The country enforced its UOG regulation after ten years of global and local in-depth analysis (Velandia, 2017). As a result, some of the

critical HSE risks have the potential to be avoided, and the remaining have a more reduced chance of occurrence. Among the essential measures to highlight are:

1. Flowback and produced water cannot be disposed to surface streams.
2. It is mandatory to disclose chemicals utilized and the identification of environmental health risks associated with their use.
3. For controlling induced seismicity, a maximum of 4.0 magnitude earthquakes is allowed before stopping operations.
4. Control and monitoring of air emissions, including methane, Vapour Oil Components, and flaring.
5. Storage of waste fluids requires the use of tanks with ceilings to avoid air emissions.
6. Neither pits nor ponds can be utilized for waste storage.
7. UOG activities in environmentally sensitive areas or close to densely populated zones are forbidden. Operations should be executed in agricultural and cattle lands.

Since 2004 the country's appealing fiscal terms have attracted IOCs after the National Hydrocarbon Agency (ANH) creation. ExxonMobil (XOM), ConocoPhillips (COP), and Drummond have shown interest in UHR development in the country, and Occidental Petroleum (OXY), Tecpetrol, Chevron Energy (CVX), Parex Resources (PXT), and Gran Tierra Energy (GTE) could follow them. They can operate alone or in association with the NOC, Ecopetrol. The Olini, La Luna, and Tablazo shales in the Middle Magdalena Valley; Los Cuervos CBM and La Luna shale in Cesar-Rancheria Basins have spurred the most significant interest from IOCs and Ecopetrol. They locate close to existing oil and gas infrastructure.

Colombia has struggled to accelerate UOG exploration and kick off development because environmental concerns strongly influence it. Among the most relevant are water sourcing and scarcity, contamination of aquifers, use of chemicals, flow-back water disposal, induced seismicity, gas emissions, health effects, and land use. The NOC (Ecopetrol) and the other three IOCs lead industry efforts to conduct the pilots. The possibility of continuing UOG activities in the country hinges on the pilot results.

Table 3 shows a UDI score for Colombia of 3.1, reflecting a country placed in the Exploration category. After analyzing the current status, we identified the country's three main factors to enhance, to generate the appropriate conditions for successful UHR

exploitation. Colombia has to improve the grading from Conventional and Other Competition (3 to 5), Geology (3 to 5), and Public Opinion (3 to 5) factors to have a score of 4.1.

A significant challenge facing the industry today is the need to obtain the LTO. UOG acceptance is needed and only will be obtained if impacted communities trust that Ecopetrol and the IOCs can operate in an environmentally, healthy, and safe manner. A window of opportunity is open after executing pilot tests defined by the government, following the recommendations from an expert commission charged with studying the UOG risks and opportunities.

There are many uncertainties related to UOG development, something usual for a technology in its infancy, especially when it is new for a basin and more for a country. Colombia can take advantage of the industry's operational learning curve, local updated and stricter regulation, industrial water reuse, and green technologies to overcome and even avoid the UHR exploitation difficulties in other countries. Moreover, given the awareness of HSE risks among stakeholders and IOCs' existence with strong cultural safety and sound operational practices involving occupational safety and process safety management, most ESG impacts should be controlled. The challenges lie in balancing the costs associated with risk mitigation and the risk tolerance level from the different parties involved. Additionally, to test the oil and gas potential and optimize the operations to reduce costs to allow financial and economic returns for the country's companies.

There is hope that the Expert Commission's recommendations in 2018 by the Government will support reinstating the previous hydraulic fracturing regulations. However, until then, the road to permitting is suspended until the pilots' results demonstrate that no harm to the environment is possible. Getting communities on board and defining and securing LTO is one of the main challenges. Unlocking the La Luna, Olini, and Tablazo formations mean maximizing belowground recovery while minimizing operations' surface footprint (Wood Mackenzie, 2019a).

In November 2018, Colombia's environmental agency, ANLA, denied an appeal by COP and Canacol Energy (CNE) to approve hydraulic fracturing projects in the Middle

Magdalena Valley Basin. The decision upholds ANLA's ruling, in which the Council of State suspended all hydraulic fracturing regulations.

7.2 Drummond Energy

Drummond Energy, Inc. is a subsidiary of Drummond Company Inc., a private own-company founded in 1985 as a coal producer. In 2004 it started exploration for CBM in Cesar-Rancheria Basin. Today it has six contracts to explore and produce natural gas from CBM and UOG resources.

In 2018 obtained the environmental and LTO to operate and successfully performed 15 vertical wells shale gas fracturing. Caporo Norte project is located in Chiriguaná and La Jagua Ibirico municipalities. It has permission to drill 57 producing and seven water injector wells and a gas pipeline of 2.8 kilometers. The production wells should have hydraulic fracturing before production starts. During 2018 the first 15 producing and one injector wells were performed. In order to obtain and secure the LTO, the operator executed several activities:

1. Strong communication strategy with stakeholders. Seventy-seven workshops before, meanwhile, and after the project finished.
2. Operational risk control voluntarily adopting the Golden Rules for the Golden Age of Gas.
3. Environmental audits from the local community.
4. Contracting most of the activities with locals.
5. Social Investment projects to improve communities' income and skills.
6. Robust monitoring of all the environmental variables.

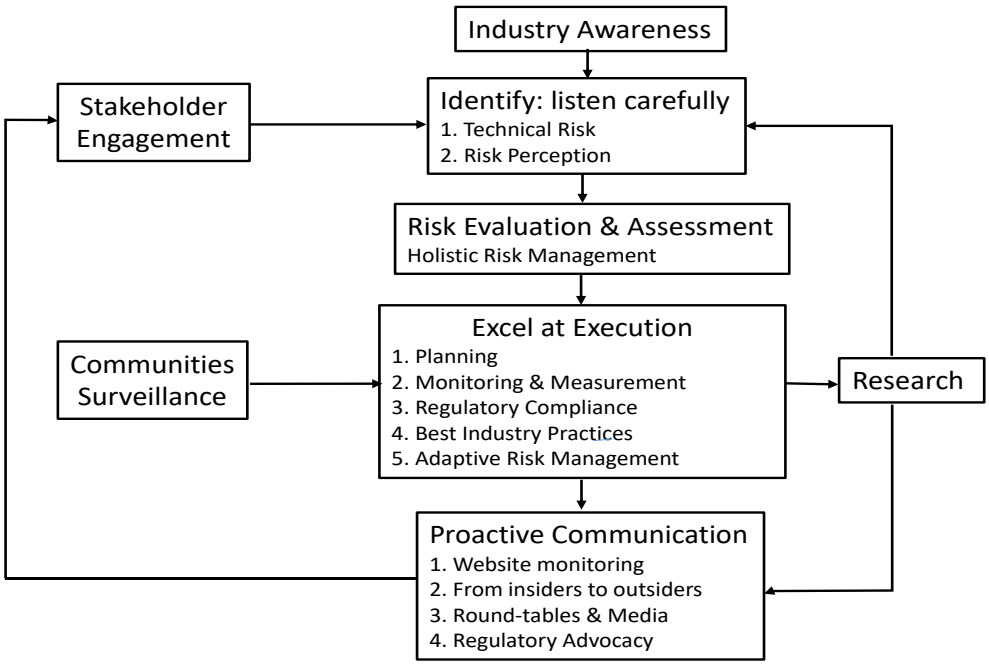
On the other side, in Colombia, Drummond and the other oil and gas companies interested in UOG development face unexpected situations after Consejo de Estado suspended hydraulic fracturing regulations. Consequently, Drummond could not continue with Caporo's field development. The company started selling equity participation or pursuing a joint venture agreement with a strong company. As part of this study, it will be possible to evaluate the strategic moves to cope with the updated regulations.

In December 2019, the Council of State ordered the ANH and Drummond to close the 15 wells at the Caporo Norte field. Authorities ruled Drummond operations, confirming the banned status for UOC activities until the pilots will perform. The Council of State's decision complicates any company's path to gain permits for any UOG work. Ecopetrol and IOC operators consistently share their view that UOG has the most considerable exploration potential of any other hydrocarbon resource play.

7.3 ESG Practices

It is essential to specify the expectations and objectives of stakeholders regarding UOG risk management. Governments, mining, oil and gas companies, local communities, regulatory agencies, unions, Not-Governmental Organizations (NGOs), academia, and society have different goals and interests. Risk management must consider these after defining a risk tolerance level that results from a balance between regulation, best operational practices, and individual expectations.

Figure 23. Five-step risk management approach to build trust and obtain the LTO in UOG operations. Source: the authors.



To determine the best risk management practices to operate safely and obtain the LTO, we had the opportunity to visit facilities, perform interviews, and evaluate reports from

Drummond energy. In Fig. 23, we synthesize our observations and literature review in a five-stage process (Zuluaga & Monterroza, 2019).

7.3.1 Industry Awareness

Several E&P companies consider the risk impact of UOG operations to be either negligible or very low. Most risks can be controlled, which is why social risk perception is the relevant subject to oversee. The challenge lies in finding a balance between the costs associated with risk mitigation and the risk tolerance level for the different stakeholders. The highest price is the impossibility of exploiting UOG resources due to a lack of environmental permits and LTO.

It is helpful to differentiate between UOG exploration and development. In exploration, the primary goals are to test hydrocarbon potential, dispel myths associated with UOG, and demonstrate that it is possible to execute operations safely. The development stage offers the opportunity to optimize costs and productivity and strengthen the operational infrastructure for ESG compliance to increase social acceptability. Additionally, it provides the opportunity for local jobs and wealth creation.

7.3.2 Listen Carefully

One best practice we observed consists of considering that every single inquiry from local communities should be listened to and resolved. Education and advocacy mechanisms are necessary, but involving local communities in the decision-making process is a considerable step to obtain the LTO. Local communities may participate through formal company presentations, roundtables, or direct observers of the company's operations and receive updated and reliable information regarding project planning, operational activities, and monitoring results.

7.3.3 Risk Evaluation and Assessment

It becomes necessary to incorporate the appropriate risk management strategy and risk assessment tool according to the level and type of uncertainty, as shown in Figure 2. Given that risk analysis does not conform to the scientific method's standard requirements, accurate risk estimations are impossible to obtain (Terje Aven, 2018). Risk analysis should contribute to each of the disciplines related to project execution from the

beginning to inform decision-makers in each step. Decisions involving stakeholders should follow the HRM approach discussed in Section 2.1.

7.3.4 Excel at Execution

The best way to build trust is through compelling and pristine exploration, pilots, and development activities. As projects evolve, accurate data and information can be obtained, and most worries should dissipate.

Complex project execution capabilities are one of the prominent skills found in top industry performers in Latin America. Companies should be outstanding at project risk management. Furthermore, companies must effectively control the supply chain, given the limitations for proppant, equipment, and material procurement in the region. As a result, it is common to use QM, JIT, and SCM to reduce costs, optimize well drilling and completion, and speed project execution. Drummond Coporo's case is an example of the process known as Scrum. It is a framework for agile, daily communication, flexible reassessment plans, innovation, project execution (Schwartz, F., 2017).

7.3.4.1 Planning

Careful design of each of stages of the project is imperative, including environmental permits, land preparation, water sourcing, well drilling and completion, hydraulic fracturing, flowback oil and water treatment and recycling, natural gas processing, electricity generation, monitoring, transportation, and storage, as well as supply chain design. Incorporating the TBL approach to include social, environmental, cost and risk dimensions in decision-making will facilitate LTO acquisition. Moreover, hiring, training, and contracting with local communities should be a top priority.

UOG is in its early stages can help smoothen the implementation of the industry learning curve and greener completion techniques and procedures to prevent negative perception. Significant advances are targeting the improvement of economic performance and the simultaneous reduction of HSE risk impacts. (Rahm et al., 2013) (Cano et al., 2015) (Gao & You, 2017a) describes some of the most relevant:

- Drilling longer horizontal wells and implementing cube development to reduce land use.
- Eliminating waste pits in drilling and completion operations.

- Reducing chemical and water consumption in hydraulic fracturing operations.
- On-site treatment technologies for recycling flow-back and produced water.
- Processing, storage, and design transportation systems for low energy consumption.
- Installing zero-venting and leak detection systems to avoid emissions.
- Adopt modular manufacturing devices to reduce cost, gain flexibility, and process the stranded gas produced in peripheral zones.

These technological advances are vital for reducing the environmental footprint by minimizing chemicals, water use, emissions, and stress within the area. The ESG goals for the oil and gas industry should aim towards zero drinking water usage, near-zero emissions, near-100% self-electricity generation, and 100% biodegradable chemical usage. Figure 23 shows the circular water management approach utilized by Drummond during the project execution.

Figure 24. Drummond's circular water management system. Source: Drummond Corporate Presentation, 2019.

7.3.4.2 Monitoring and Measurement

The main advantage of monitoring is the supply of information to avoid risk occurrence. The most powerful way to demonstrate UOG exploration and development's actual impact is by offering real-time data to the industry, regulators, and the public. Combined with a

baseline, it will be possible to evaluate the impact of operations in surface and groundwater, induced seismicity, air quality, biodiversity, and other subjects.

When a baseline is not available, sampling should be done before, during, and after drilling and completing a new oil or gas well. Colorado was the first state in the US to require groundwater monitoring before starting drilling and completion activities (Son et al., 2018). In Colombia, the Expert Commission appointed in 2018 by the Government recommended that pilots carry out to answer environmental and social concerns. As a result, companies should have a real-time monitoring network designed for data acquisition, transfer, administration, analysis, interpretation, and display results.

Drummond built a baseline four years in advance of the pilot. Additionally, to obtain the LTO and regulatory compliance, the company performed real-time monitoring sampling before, during, and after drilling and completing CBM wells. They tested surface and underground water, seismic activity, and air quality based on lab-qualified surrogate technologies. Local workers performed surface water sampling and other tasks. As a result, communities were aware of the operational activities and the actual environmental impact, which was a powerful tool to build trust and avoid nonfactual news.

7.3.4.3 Regulatory Compliance

The regulatory burden is a result of government energy policy and political climate. In the US and Canada, efforts have been made to enforce federal oversight, given environmental impact and public discontent, with varying success. Additionally, there is a commitment to reduce methane emissions in 2025 by at least 40% from 2012 levels in Canada. Regulation in Latin America is stricter in several aspects compared to North America due to public pressure. Legislation in Australia is more mature for CBM than for shale gas. Development in the European Union has been slow; energy policy is broadly a member state competence (Bakshi, 2017, p.131). Several European Union countries have banned UOG activities for the time being. The United Kingdom did it in 2019 after the first shale gas exploration well drilled in Lancashire in 2011, and a failure pilot test followed.

Oil and gas companies should comply with regulations and proactively communicate to the public those efforts because there is a common perception that regulatory agency

surveillance is weak. Moreover, companies should find a way to offer access to reports, fines, and other relevant documentation for public scrutiny.

7.3.4.4 Best Operational Practices

Given the awareness of HSSE safety risks among stakeholders and global oil and gas companies with strong cultural safety and sound operational practices involving Occupational Safety and Process Safety Management, most of the risk impact should be controlled effectively. To avoid operational safety problems such as injured workers, well integrity leaks, blowouts, and spills, oil companies must demonstrate safety practices in an ESG culture. Residual risk should be managed by implementing additional measures until reaching the established tolerance level.

Adopting the best operational practices beyond regulation despite higher associated expenses is another way for companies to obtain the LTO by performing in line with higher industry standards. Some alternatives that follow from these voluntary industrial procedures are:

1. Effective hazard risk management.
2. Monitoring, measuring, and controlling environmental impacts.
3. Zero drinking water usage and rigorous assessment, monitoring, and water handling requirements.
4. Robust procedures for well design, drilling, cementing, and integrity testing.
5. Reliable data gathering from baseline and monitoring and academic involvement to generate credible studies.
6. Venting elimination and flaring minimization.

Common practice from most IOCs is to halt operations anytime a deviation of critical parameters is detected or if a person, the environment, or an asset is somehow affected due to operational activities. One example is the ExxonMobil Water Resources Management Guide (Lunn et al., 2014).

7.3.5 Proactive Communication

Early and effective communication is critical to generate long-term trust, especially if perceived risks are deemed complex, uncertain, or ambiguous. Most organizations lack the capabilities to design and implement effective risk management strategies to assess

plural values and interests and communicate with relevant stakeholders. Those social needs should be integrated into engineering thinking when assessing risks and comprise another
characteristic of resilient organizations. A set of discursive management tools and case studies, including UOG development, are published by The IRGC (IRGC, 2014).

Several measures can help to improve communications among stakeholders for UOG exploration and development in Latin America. First, it is necessary to educate all the interested parties and the public on the UOG general practice, including environmental nuisances. A unique institutional web page with relevant information can be helpful to avoid misunderstandings and data manipulation. Educate journalists to understand the industry's realities to avoid nonfactual coverage lacking credibility and support. One way to deal with this reality is to create and strengthen research groups in partnership with academia and address questions and requests from government institutions and other parties. Figure 23 shows the stages where we recommend research involvement.

Second, perform fully monitored pilot tests, including a complete baseline to measure the full scope of potential environmental impacts. A compelling way to reduce ambiguity is through reliable and updated information. Research and case studies depicting UOG experiences in other countries cannot be relied on but are helpful as references to consider.

Third, consider the full scope of risk expectations from all stakeholders involved and understand their perspective as a key to improving communication. It is essential to avoid using research that does not represent the situations under discussion and ensure that all relevant parties are involved. A good practice is to advocate education and communication from the inside out through informative meetings, starting from employees, and progressively to reach out to contractors, local communities, authorities and media, regulatory agencies, academia, NGOs, governments, and society.

Fourth, make full transparency with regards to planning and operations a top priority. Firms should release information regarding potentially toxic contaminants in flowback fluids, volumes and sources of water, and water disposal, including seismic

measurement, sustainability efforts, job creation, and related activities. Other measures involving communication and trusting are:

1. Early and sustained engagement with leading stakeholders.
2. Mutually agreed on direct community investment to integrate different actors to fulfill specific needs when required.
3. Promote the sharing of oil rent benefits with locals.
4. Enforce community adaptation.

For governments and sponsoring UOG activities, we recommend several strategies to create a balance between governmental energy policy, industrial activities, and the involvement of local communities.

7.3.6 Enforce stricter regulations and governmental control capabilities where needed

Governments should enforce laws to protect environmentally sensitive areas or cultural landmarks. Colombia updated its UOG regulation after three years of international and domestic in-depth analysis. As a result, some of the critical HSE risks have the potential to be avoided, and the remaining have a lower chance of occurrence (Velandia, 2017, 63). Among the most important factors to highlight are:

1. Dispose flowback and produced water out of surface streams.
2. Disclosure of chemicals used in hydraulic fracturing operations and identifying HSE risks associated with their use are mandatory.
3. Several measures to control induced seismicity ruling hydraulic fracturing and wastewater injection are enacted; for instance, a maximum of 4.0 magnitude earthquake is allowed before stopping operations.
4. Control and monitoring of air emissions, including methane, VOCs, and flaring.
5. Storage of waste fluids requires tanks with ceilings to avoid air emissions; neither pits nor ponds can be used for waste storage.
6. UOG activities in environmentally sensitive areas or close to densely populated zones are forbidden; perform operations out of agricultural or cattle lands.

7.3.7 Strength environmental, health, and safety baselines

A lack of baseline data has been a source of frustration for several regulators and researchers. They comprise the conditions of surface and subsurface water sources,

seismic activity, air quality, land use, biotic diversity, and socio-economic activities from the immediate vicinity in which UOG activities are under consideration. Baselines are fundamental to facilitating the evaluation of UOG activities' impact on local resources such as streams where waste might be disposed (Bakshi, 2017, p.43).

7.3.8 Stability in regulatory and economic incentives

Economic stability is vital for companies to ensure financial returns and avoid the temptation to reduce the necessary resources for monitoring, Occupational Safety, and Process Safety Management. The stability of hydrocarbon prices, macroeconomic activity, contracts, rules, and regulation contributes to the climate of investment and facilitates long-term relationships among stakeholders.

7.4 Antifragile Attributes Grading

We present a similar analysis and considerations to the ones described in Section 7.4 for Drummond Energy, Inc.

Table 7. Drummond's Resilience and Antifragility Attributes. Source: the authors.

	Infrastructure		Comments
Resilience	Parent		Drummond Company Inc - Private own
		Financial Strenght	No debt. Financial resources through equity.
		People	6.000 employees in Colombia
		Supply Chain	Suppliers from local firms. Specialized directly from the US
		Redundancy	Equipment and facilities fit the operational needs
		Vertical Integration	Local coal mining operations

		Portfolio	Operations concentred in Alabama (US) and six blocks in Cesar-Rancheria Basin
	Local		
		Modularity	Executive Action Teams to develop Coporo Project; 30 people per Team
		Capabilities	
	Managerial		
		Leadership	Clear roles and responsibilities
		Governance	Drummond Energy Inc. independent company; Action Teams
		Adaptive Risk Management	Project executed by steps with updates after new information from wells
		Communication	All personal understand the goals and priorities
	Technical		
		Risk Assessment	Operational and HSE risk management according to standard industry practices
		Decision Making	No evidence
		Project Execution	Cost and Schedule control
		Best Practices & Standards	Golden Rules for the Golden Age; ISO: 14.001, 18.001, 26.000 and 55.000
		Culture	

		Responsibility	Autonomous Action Teams; Better Coal Certification
		Autonomy	Small scale operation
		Collaboration	Strong interaction among Design, Planning, Project Execution, and Production
		Agility	Small scale operation
Antifragility	Adaptation	Innovation	Drilling, Completion, and Production adaptations to improve efficiencies
		Learning Organization	Transfer from CBM US activities. Scrum framework application.
		Flexibility	Private Company. Adjust operations according to the needs
	Growth	Optionality	Expand, Abandon, Execution by steps
		Diversification	Limited USG possibilities outside Colombia. Possibility to switch oil to gas
		Sustainability	Best in class ESG strategy
	Quality	High Performance	Coporo Norte development way ahead of peers
		Efficiencies	A culture focused on cost control and efficiencies. Drilling time reduced from 10 to 6 days
	Hormesis	Small Risks (Trial and Error)	Constant design, planning, execution test to improve efficiency and gain productivity
		Stressors	Cost control and project goal accomplishment

8 ANTIFRAGILE FRAMEWORK PROPOSAL

When doing a qualitative case study research that no relies on statistical benchmarks, finding other ways of thinking about such criteria is necessary. In Section 1.4, we point out how the multi-method offers the possibility to use the same logic as the one used in multiple experiments. A significant finding could be replicated by conducting a second and a third, and even more experiments (Yin, 2018, p.54). The difference between the replication logic and the sampling logic is associated with the different and specific environmental contexts where the surveyed firms act. It makes the application of the former impossible to use, given the innumerable number of potentially relevant variables that would require an impossibly large sample of cases, too large to allow more than a superficial examination of any given case.

When a theory exists, each case must be carefully selected so that each of the individual cases predicts similar results (a literal replication). Since the selected cases are Exploratory, we evaluate them by contrasting results, looking for theoretical replications. We analyze the identified antifragile Small-C and Medium-C firms' behavior. The case studies (Drummond and Tecpetrol) evaluate the Attribute details and tactical responses. The Medium-C, the strategic and tactical responses to the extreme events, and only a few Attributes. Overall, we obtain theoretical replications that we define in the form of working hypotheses, leaving the task for future research studies to obtain literal replications.

Four tests are commonly used to establish the quality of most empirical social research: Construct validity, internal validity, external validity, and Reliability (Yin, 2018, p. 42). In this study, we construct validity by evaluating 77 companies, 51 transactions, and 26 firms filing for chapter 11 protection. Additionally, we assess the performance of 24 organizations in Latin America. The internal validity comes from pattern matching and explanation building in Chapters 7,8 and 9. The external validity shows with the use of replication logic in the multiple-method research analysis. We maintain a chain of

evidence for all the documentation to ensure Reliability, a good practice for qualitative research analysis.

8.1 Adaptive Strategies

It is not simple to evidence resilience and adaptative response to extreme events in the short term since almost all companies curtail production and reduce costs. These measures could reflect either operational flexibility or financial distress, making it challenging to evaluate. Moreover, some companies behave conservatively while others aggressively in response to the collapse hydrocarbon price crisis.

Nevertheless, it is possible to portray the leading strategies and tactics followed for oil and gas firms to face the 2019-2020 extreme event, in response to the stakeholder needs, after reviewing the 2Q 2020 reported operational and financial results. Almost all the players showed positive cash flows, thanks to a combination of tactics such as capital expenditure reduction, cost savings, hedging, and production curtailment. Some claimed annual cost reductions of up to 25%, but most are not sustainable because they depend on deflation instead of current efficiencies. We analyze Antifragile, Resilient, and Fragile behavior during the first semester of 2020 by tracking the firm's short-term responses to identify main strategies and adaptability.

Table 8. Adaptative Strategies and Tactics followed for oil and gas firms in North America. Source: the authors.

		Companies	
Strategy	Scope	US	Canada
Switch Option	Basins	< Bakken CLR, XOM, HES, COP, WPX > Barnett TOT, EOG	> Montney CNQ, COP
	Gas / Oil	SWN, CHK	CR, CNQ
	International	APA, HES, EOG	BTE, VET, ERF
	Service Companies	XOM, CVX	
Vertical Integration	Up/Mid/Downstream	XOM, CVX	SU, IMP, CNQ, CVE, HSE
Cost Reduction	Deflation	All companies	All companies

Table 8. Adaptative Strategies and Tactics followed for oil and gas firms in North America. Source: the authors. (Continuation)

	Technology	EQT, SWN, RRC, AR, CNX, FANG, PXD	BIR
	Efficiencies	MRO, PE, PXD, CXO, EOG	POU
Risk Management	Hedging	All except by COP, CLR	All except by CNQ, CVE, IMO, HSE
	Storage oil production	HES	CNQ
Scale Option	Capex Reduction	All companies	All with <20% TOU, VET, BIR, PEY, CNQ
	Decline rate moderation	PE	VII
	Production Curtailment	All companies	All companies
Improve Financial Condition	Sell Assets & ORRI	RDS, RRC, DVN, AR	
	Working capital	EOG	
	Refinancing/Debt Payment	EQT, CNX, PXD, AR, RRC, SWN	VII, PEY
	Dividends Curtailment	RDS, WPX, CLR, BP, MRO	SU, CNQ, CVE, HSE, TORC
	Chapter 11	WLL, XOG, CHK, CRC, DNR	
	Improve debt for liquidity	FANG, EOG, XOM, CRK, PXD	HSE, CVE, CNQ, SU
Growth	Asset/Company Acquisition	CVX, COP	TOU, CNQ

8.1.1 Diversification

Portfolio diversification becomes a critical element of resilient organizational behavior. Table 8 shows the different company strategies depicted in the 2Q 2020 reports. The critical aspects to evaluate are asset quality, size, and synergies from proximity and infrastructure access. Fields with lower breakeven and access to the most attractive markets are preferred.

Companies with geographic span through different US Basins (DVN, MRO, EOG, OXY, XOM, APA, OVV), oil and gas assets (XOM, EOG, APA, OVV, SM, CXO, XEC), International exposition (BTE, VET, ERF, HSE, APA, HES, MRO, NBL) or vertical integration (XOM, CVX, SU, IMP, CNQ, CVE, HSE), have the flexibility to switch focus and prioritize activities according to their needs. Additionally, they have economies of scale and natural hedging for lower prices and infrastructure and market restrictions.

8.1.2 Growth

Antifragile firms increased production, avoiding external financing by acquiring assets opportunistically on internal cash generation.

1. Firm acquisitions: Chevron Energy (CVX) to Noble Energy (NBL); Canadian Natural Resources (CNQ) to Painted Pony (PONY).
2. Asset acquisition: ConocoPhillips (COP) Montney acreage to Kelt Exploration (KEL).

EOG Resources (EOG) and Cabot Oil & Gas (COG) strategy focus on organic growth and seldom execute mergers and acquisitions. Pioneer Natural Resources (PXD) and EOG promised to deliver 5-10% annual production growth from their asset portfolio through internal cash generation. CVX, PXD, and CNQ were the only ones showing relevant production growth. ExxonMobil (XOM), EOG, and COG followed a more conservative approach and decided to keep a consistent and growing dividend at the expense of production gains.

Resilient companies could keep and even slightly increase output, despite the low prices and high uncertainty. The best performers were Hess Corp (HES), Diamondback Energy (FANG), and Parsley Energy (PE) in the US. Antero Resources (AR) and Southwestern Energy (SWN) increased production on better natural gas prices. These short-term results reflect a resilient behavior but depend on better natural gas prices and the possibility of generating positive cash flows utilizing hedging.

Canadian companies looked better prepared than their peers in the US since the crisis started early due to infrastructure limitations. Fragile companies ARC Resources (ARX), Whitecap Resources (WCP), Vermilion Energy (VET), Birchcliff Energy (BIR), and the Robust Tourmaline Oil (TOU) and Cenovus (CVE) showed resilience behavior. Additionally, Canadian Natural Resources (CNQ) exhibited antifragile behavior. Those

early results suggest that the organizational resilience grading to rank Canadian companies could be adjusted once additional information from longer-term behavior is available.

Fragile organizations were those 22 oil and gas companies that Courts granted Chapter 11 protection during the first semester of 2020. Five of them belong to the 77 companies in the sample for this study: Whiting Petroleum (WLL), Extraction Oil & Gas (XOG), Chesapeake Energy (CHK), California Resources (CRC), Denbury Resources (DNR). Oasis Petroleum (OAS) is the sixth company filed by the end of September. 2019 Z-Score was negative for four of them, 0.26 for DNR, and 0.54 for OAS. Additionally, CVX and CNQ acquired Noble Energy (NBL) and Painted Pony (PONY) because of their natural gas assets and financial distress.

8.1.3 Optionality

Short-term tactics and strategies involve strengthening the asset portfolio to limit downside risk and take advantage of opportunities, what Taleb named 'Barbell Strategy,' described in Section 2.2. This approach, also known as real options portfolio, was followed for successful firms in highly uncertain environments (Johnathan Mun, 2006), (Bravo et al., 2008). Tables 8 and 9 analyze the different real options and tactics utilized for antifragile companies in North and Latin America.

Table 9. Optionality showed for antifragile oil and gas companies in Latin America. Source: the authors.

		Companies					
Strategy	Scope	COP	XOM	CVX	Tecpetrol	VIST	Drummond
Countries with Unconventional Operations		3	2	1	1	1	1
Switch Option	Basins	0	0	0	0	0	0
	Gas / Oil	0	0	1	1	0	1
Vertical Integration	Up/Mid/Downstream	0	1	1	0	0	1
Cost Reduction	Self-Organization	0	0	1	1	1	1
	Technology	1	1	1	1	1	1
	Efficiencies	0	0	1	1	1	1

Table 9. Optionality showed for antifragile oil and gas companies in Latin America. Source: the authors. (Continuation)

Risk Management	Hedging	0	0	0	0	0	0
	NOC Joint Venture	1	1	1	0	0	0
Scale Option	Cost Reduction	0	1	1	1	1	1
	Project downscale	0	0	0	1	0	0
	Production Curtailment	0	1	1	1	1	0
Project Execution	Operator	3	0	0	1	1	1
	Non-Operator	0	2	1	0	0	0
Growth	After 2019-2020 Events	0	1	1	1	1	0

8.1.4 Sustainability

There is little evidence of Sustainability resilient organizational attributes in the research literature. The oil and gas industry shows evidence to demonstrate the need for ESG goals and green practices to gain investors and stockholders' interest.

European oil and gas companies are at the forefront of the energy transition. After the 2019-2020 extreme event, BP Petroleum (BP) announced that it would grow low-Carbon investment by ten: renewables, bioenergy, hydrogen and carbon capture, utilization, and storage, as means to achieve the 2050 “net zero” output goal. This move would imply transforming its portfolio, declining upstream production by 40%, divest assets, no longer exploring in new countries, and a 20% refinery throughput reduction by 2030. The company reduced dividends by 50% to finance these plans, which received shareholders’ blessing, a step toward the antifragile organization. Other European oil and gas companies follow BP’s lead and have ambitious ESG goals: Repsol Energy (REP), Total Energy (TOT), and Equinor ASA (EQNR).

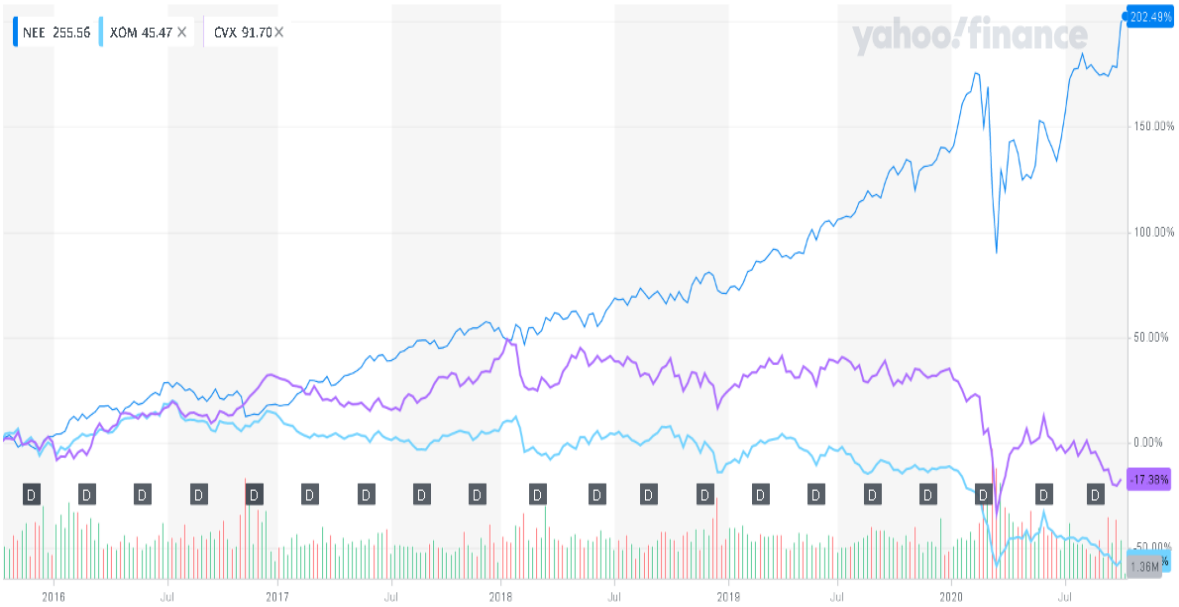
Table 10. Sustainability CO2 report from Canadian companies. Source: the authors.

Canadian O&G Firm Emission Intensities GHG Intensity (KgCO2e/BOE)		
Canadian Natural Resources (NYSE)	CNQ	63.7
Cenovus Energy (NYSE)	CVE	50.1
Imperial Oil (NYSE)	IMO	100.6
Suncor Energy (NYSE)	SU	82.3
ARC Resources	ARX	18.5
Crescent Point Energy (NYSE)	CPG	40.9
Enerplus Corp (NYSE)	ERF	29.5
MEG Energy Corp	MEG	67.0
Seven Generations Energy Ltd	VII	14.4
Tourmaline Oil Corp	TOU	17.4
Vermilion Energy (NYSE)	VET	28.8
Whitecap Resources	WCP	51.0
Advantage Oil & Gas	AAV	13.0*
Athabasca Oil	ATH	40.0*
Baytex Energy Corp	BTE	45.7
Birchcliff Energy Ltd	BIR	11.3
Nuvista Energy Ltd	NVA	20.2
Peyto Exploration & Development Corp	PEY	22.2
TORC Oil & Gas	TOG	46.8

Organizational Sustainability, Antifragility, and sustainable development are part of a new tendency to move from fragile unsustainable activities to antifragile ones and getting approval from stakeholders and investors (Linnenluecke & Griffiths, 2010) (Platje, 2015) (Winston, 2017). Another example constitutes the way NextEra Energy Inc (NEE) overtook XOM and CVX as the largest energy company in the US by market value. The world's biggest wind and solar power producer surpassed CVX and XOM in October

2020, leading for the first time the race between renewables and fossil fuels on climate change.

Figure 25. 5 year Stock Price comparison XOM, CVX, and NEE. Source: YahooFinance, 2020.



8.2 Antifragility Framework Validation and Development

In Section 1.1, we allude to the lack of a clear conceptualization of organizational antifragility. A construct demands clarifying its definition, scope conditions, contextual relations, attributes, framework, and casual relationships. Theory building requires clearly defined conceptual categories to encourage researchers to generate more effective research questions, apply appropriate and epistemologically consistent methods, and identify exceptions to the categories that open opportunities for future research (Academy of Management, 2010).

An essential goal of this study is to give initial thoughts and ideas for this challenge. The mixed-method research method allows identifying and evaluating several Antifragile organizations in North and Latin America. We studied the North American firms ConocoPhillips (COP), Chevron (CVX), ExxonMobil (XOM), EOG Energy (EOG), and

Pioneer Energy (PXD). COP, CVX, XOM have subsidiaries in Argentina, Colombia, and Chile, as shown in Table 9. In Latin America, we perform case study research for Drummond Energy and Tecpetrol. Table 11 shows the relationship between strategy, scope, and critical framework attributes.

Table 11. Antifragility Framework Attributes followed for O&G Companies. Source: the authors.

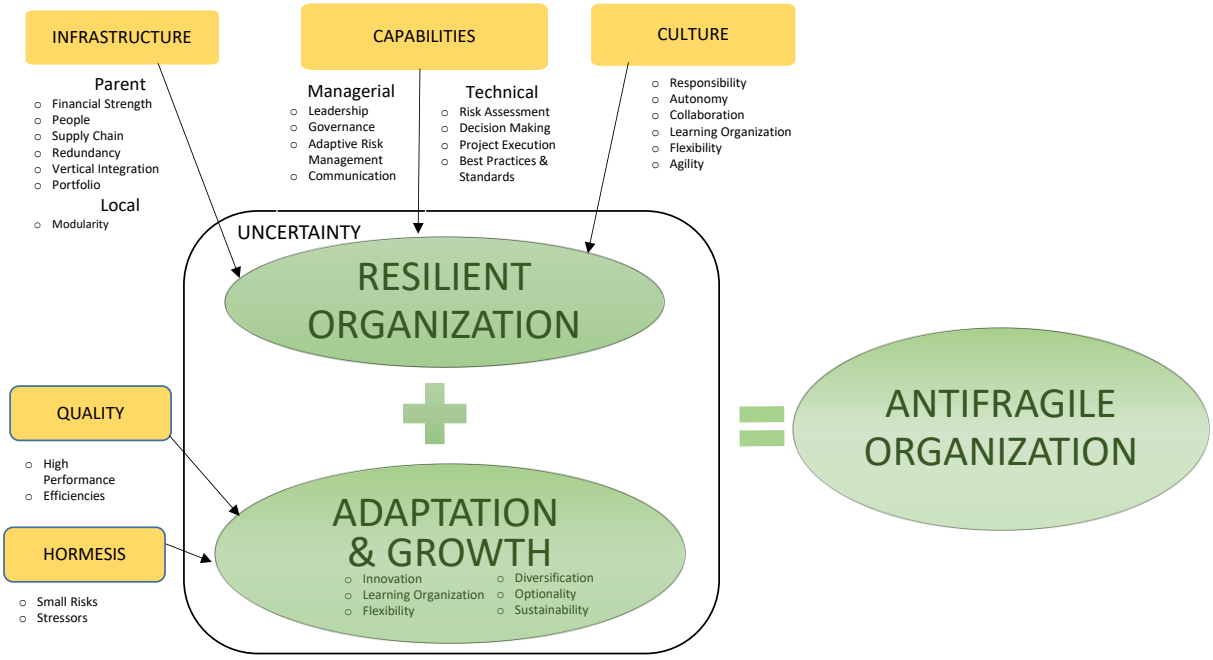
Strategy	Scope	US	Canada	Argentina	Colombia	Chile	Framework
Number of Antifragile Companies		6	1	5	3	1	
Vertical Integration	Integrated	XOM, CVX, COP	CNQ				Parent Support
	Upstream	EOG, COG, PXD		Tecpetrol, VIST, XOM, COP	Drummond, COP		
	Joint Venture with NOC	No Possible		CVX	XOM	COP	
Diversification	Basins	XOM, CVX, COP, EOG	CNQ				Diversification
	Focused (one basin)	COG, PXD		All	All	All	Local
	Service Companies	XOM, CVX					Diversification
Cost Reduction	Cooperation (Knowledge Sharing)	Yes	Yes	Yes	No	Yes	Collaboration
	Technology - Efficiencies	All	All	All	All		Learning Organization

Table 11. Antifragility Framework Attributes followed for O&G Companies. Source: the authors. (Continuation)

	Trial and error	All	All	All	All		Adaptive Risk Management
	Midstream access	COP, XOM, CVX	CNQ	Tecpetrol, CVX	XOM		Efficiencies
	Quality Management	Best Practices		Self-Development			Quality
Risk Management	Hedging	PXD					Risk Management
	Joint Venture NOC			CVX	XOM	COP	Diversification
Optionality [Option name]	First Movers [Growth]	EOG	CNQ	CVX	COP, XOM	COP	Hormesis
	[Execution by Stages]	All	All	All	All	All	Modularity
	[Switch] Production (Gas/Oil)/Basin	EOG, COP	CNQ	Tecpetrol			Adaptation
	Project downscale [Wait]	XOM, CVX, COP, EOG	CNQ	Tecpetrol			Flexibility
	Production Curtailment [Reduce]	All	CNQ	All			Agility
Infrastructure	Size (Economies of Scale)	XOM, CVX, COP; EOG					Resilience
	Financial Strength	All	CNQ	All	All	COP	
	Project Execution	All	All	Tecpetrol, XOM, VIST	Drummond		Project Execution
	Resources / Redundancy	All	CNQ	Tecpetrol	Drummond		Parent Redundancy
ESG	GHG /Water use Report	EOG, COP	CNQ		Drummond		Sustainability
	License to Operate	Not required yet			Drummond		

We contrasted our findings and updated the theoretical antifragility model described in Chapter 2. Figure 26 shows the proposed framework.

Figure 26. Organizational Antigrafility Framework. Source: the authors.



8.3 Propositions, Casual relationships, and Hypotheses

After the study propositions we set in Section 1.2 and the empirical evidence we collect and analyze, we propose the following working hypotheses:

- Antifragile Organizations are a summation of Resilience and Growth financed with internal resources.
- Antifragility Framework is a combination of Resilience, Growth, Hormesis, and Quality.
- Altman's Z-Score is the most appropriate indicator to measure an Organization's Resilient maturity level after an extreme event.
- The more feasible growth indicators are the five-year EBITDA CAGR for Mature Organizations and Time-to-production for Emergent ones.
- Local and International antifragile organizations structure as a resilient parent company, mid-size Divisions (locally) or Subsidiaries (Internationally), and small autonomous teams.

9 CONCLUSIONS AND FUTURE WORK

9.1 Conclusions

Resilient organizations possess a strategic fit to bolster knowledge and sustainability, diversifying and allocating capital into flexible, lower cost, high return, and zero-carbon assets, increasing their ability to deal with high uncertainty.

Antifragile companies are Resilient and can additionally grow once the conditions exist. On the contrary, Fragile organizations have financial distress, high costs, difficulties adapting, and are prone to bankruptcy after a disruptive event.

Asset quality, diversification, optionality, efficiencies, and effective project execution are the main drivers to propel top performance and the ability to take advantage of the opportunities existing after extreme events.

One of the goals of this study was to identify and evaluate customarily financial and operational metrics useful to measure organizational resilience after a disruptive event. The two hydrocarbon price collapses from the last decade that affected the unconventional oil and gas development in North America allowed us to evaluate the firm's resilience through their recovery capabilities.

We identify and evaluate customarily financial and operational metrics useful to measure organizational resilience after a disruptive event. The two hydrocarbon price collapses from the last decade that affected the unconventional oil and gas development in North America allow us to evaluate the firm's resilience through their recovery capabilities.

Altman's Z-Score financial ratio is the most appropriate for resilience measurement, together with a set of metrics applicable to evaluate antifragility and ESG capabilities.

Firms that regain an Altman's Z-Score of 3.0 (three) or higher in less than three (3) years without external financing are the most resilient. It matches market capitalization gain for the same companies during the evaluation period, suggesting utilizing Z-Score as a proxy for value generation. Also, together with EBITDA or production growth, it allows us to identify and measure antifragile behavior, representing the possibilities to withstand the crisis and flourish when hydrocarbon prices recover. We observe a Z-Score lower to 1.0 (one) before the crisis, meant to be in bankruptcy without additional financial funding after no more than three years.

For the international context, without detailed financial information, we propose to utilize the parent company Z-Score combined with output growth to evaluate resilience in high uncertainty environments. In Latin America, we noticed that antifragile firms have resilient parent companies and the lowest time required for resource development and production growth.

Oil and gas companies can effectively mitigate operational, HSE, and social risks by incorporating strict regulation compliance, leading-edge technologies, best practices in operations, engagement with stakeholders, effective communication, and direct community investment. Moreover, by employing an antifragility approach incorporating resilience, optionality, hormesis, and risk-taking, companies can capture the underlying opportunities within uncertainty.

Energy security is the main economic and strategic concern for those nations depleting conventional hydrocarbon production or importing energy supplies. However, there are significant barriers that countries should overcome to obtain commercial UHR exploitation. Nations like Russia, China, and Saudi Arabia, where NOCs are addressing the challenge to exploit UHR on their own, lack the technology and knowledge required, despite having strong governmental support and capital availability. On the contrary, the way Argentina, Oman, and Turkey are attracting IOCs to work together with their NOCs allows them to emulate the North American results. Eslovenia and Chile have exploits UHR without IOCs by learning abroad and adapting local industry practices.

We have identified the critical factors required for UOGD and modeled them utilizing the UDI to demonstrate that it is mandatory to fulfill most of them to develop UHR

commercially. Researchers and policymakers can utilize UDI to objectively evaluate the possibilities and requirements for any given country to exploit its UHR potential. With more countries working actively to exploit unconventional resources, it will be possible to update the index to reflect new requirements, challenges and technologies and offer deeper insights regarding evolving critical factors for UHR exploitation.

Colombia is in the right way to attract the IOCs together with its NOC. However, it requires testing UHR successfully and demonstrating that applying the best technologies can do it economically and environmentally friendly to obtain public support. The future of UHR development in Colombia will depend on a combination of different factors. The oil and gas industry demonstrates environmental and safe sustainable practice, confirmation of favorable resource potential, the ability to obtain low-cost operation after complying with regulation and solve logistic challenges, and public support. The latter is the most significant determinant.

For oil and gas companies to obtain the LTO, the economic balance perceived by stakeholders between the benefits of UOG development and the costs of social and environmental impacts and externalities should be positive. The future of UOG development in Latin America will depend on a combination of different factors. The oil and gas industry must demonstrate sustainable environmental and safe practices, confirm favorable resource potential, obtain low-cost operation after complying with regulation, solve logistic challenges, and obtain public support.

A significant challenge facing oil and gas companies in Latin America is the need to obtain the LTO. Acceptance of UOG operations is required and can only be obtained once local communities can trust the industry's efforts to operate in an environmentally, healthy, and safe manner. Besides, the wealth generated from oil and gas resources will have to be distributed equitably among all stakeholders involved. Communication should be reliable, direct, and transparent, empowering people with accurate information.

A five-step risk management approach facilitates the obtainment of the LTO for oil and gas companies. The five proposed stages are (1) Industry awareness; (2) Listen carefully; (3) Risk evaluation and assessment; (4) Excel at execution; and (5) Proactive communication.

9.2 Future Work

Ecological sustainability and financial distress after Covit-19 are factors not evaluated in this study because their impact is still unknown. Their role around the world will be critical for UHR in the foreseen future. Companies and countries able to successfully manage them will possess a distinctive competitive factor. Future studies should consider those aspects and update the results.

Further research is required to understand better the attributes common to antifragile organizations and the performance-risk metrics to use for subsidiaries and joint ventures. It is also relevant to have additional empirical studies to reinforce Altman's Z-Score parameter use for organizational resilience measurement and the scale utilized for resilience classification.

COMENTARIO CON VISTO BUENO DEL DIRECTOR

FIRMA DEL PROPONENTE

Óscar Bravo Mendoza

FIRMA DEL DIRECTOR

Diego Fernando Hernández Losada

FECHA

20 de Noviembre de 2020

BIBLIOGRAPHY

Adamus, W., & Florkowski, W. J. (2016). The evolution of shale gas development and energy security in Poland: Presenting a hierarchical choice of priorities. *Energy Research and Social Science*, *20*, 168–178. https://doi.org/10.1016/j.erss.2016.08.010

Altman, E. I., Iwanicz-Drozdowska, M., Laitinen, E. K., & Suvas, A. (2017). Financial Distress Prediction in an International Context: A Review and Empirical Analysis of Altman's Z-Score Model. *Journal of International Financial Management and Accounting*, *28*(2), 131–171. https://doi.org/10.1111/jifm.12053

Aven, T. (2014). *Risk, Surprises, and Black Swans*. Routledge.

Aven, T., & Kristensen, V. (2005). Perspectives on risk: Review and discussion of the basis for establishing a unified and holistic approach. *Reliability Engineering and System Safety*, *90*(1), 1–14. https://doi.org/10.1016/j.ress.2004.10.008

Aven, Terje. (2012). The risk concept-historical and recent development trends. *Reliability Engineering and System Safety*, *99*(0951), 33–44. https://doi.org/10.1016/j.ress.2011.11.006

Aven, Terje. (2015a). Implications of black swans to the foundations and practice of risk assessment and management. *Reliability Engineering and System Safety*, *134*, 83–91. https://doi.org/10.1016/j.ress.2014.10.004

Aven, Terje. (2015b). The concept of antifragility and its implications for the practice of risk analysis. *Risk Analysis*, *35*(3), 476–483. https://doi.org/10.1111/risa.12279

Aven, Terje. (2016). Risk assessment and risk management: Review of recent advances on their foundation. *European Journal of Operational Research*, *253*(1), 1–13.

https://doi.org/10.1016/j.ejor.2015.12.023

Aven, Terje. (2017a). How some types of risk assessments can support resilience analysis and management. *Reliability Engineering and System Safety*, *167*(March), 536–543. https://doi.org/10.1016/j.ress.2017.07.005

Aven, Terje. (2017b). How some types of risk assessments can support resilience analysis and management. *Reliability Engineering and System Safety*, *167*(March), 536–543. https://doi.org/10.1016/j.ress.2017.07.005

Aven, Terje. (2017c). What Defines Us as Professionals in the Field of Risk Analysis? *Risk Analysis*, *37*(5), 854–860. https://doi.org/10.1111/risa.12680

Aven, Terje. (2018). An Emerging New Risk Analysis Science: Foundations and Implications. *Risk Analysis*, *38*(5), 876–888. https://doi.org/10.1111/risa.12899

Aven, Terje, & Krohn, B. S. (2014). A new perspective on how to understand, assess and manage risk and the unforeseen. *Reliability Engineering and System Safety*, *121*, 1–10. https://doi.org/10.1016/j.ress.2013.07.005

Aven, Terje, & Renn, O. (2015). An Evaluation of the Treatment of Risk and Uncertainties in the IPCC Reports on Climate Change. *Risk Analysis*, *35*(4), 701–712. https://doi.org/10.1111/risa.12298

Bakshi, V. (2017). *Shale Gas* (Second). Global Business and Business Limited.

Benaben, F., Montreuil, B., Gou, J., Li, J., Koura, I., Mu, W., Benaben, F., Montreuil, B., Gou, J., Li, J., Lauras, M., & Tentative, A. (2019). *A Tentative Framework for Risk and Opportunity Detection in A Collaborative Environment Based on Data Interpretation To cite this version : HAL Id : hal-01988039*.

Bjerga, T., & Aven, T. (2015). Adaptive risk management using new risk perspectives - An example from the oil and gas industry. *Reliability Engineering and System Safety*, *134*, 75–82. https://doi.org/10.1016/j.ress.2014.10.013

Bond, C. J. (2014). Positive peace and sustainability in the mining context: Beyond the triple bottom line. *Journal of Cleaner Production*, *84*(1), 164–173. https://doi.org/10.1016/j.jclepro.2014.01.033

Bravo, O., & Hernandez, D. (2020a). Critical Factors for Unconventional Hydrocarbon Resources Development. *CT&F - Ciencia, Tecnología & Futuro*, *10*(2). InPress

Bravo, O., & Hernandez, D. (2020b). Risk Management Strategies Required for Unconventional Oil and Gas Exploration and Development in Latin America. *SPE-199430-MS*, 16. https://doi.org/10.2118/199430-MS

Bravo, O., Mogollón, L., & Parra, J. (2008). *Valuation of a Real Options Portfolio*. http://www.realoptions.org/papers2008

Bravo, O., & Sanchez, M. (2012). *Gestión Integral de Riesgos - Tomo 2* (Bravo & Sá).

Brezuleanu, S. et al. (2015). Relationships between Fashion Enterprises Resilience under Market Disruption and Employees' Creative Involvement and Wellbeing Degree. *Revista de Cercetare Şi Intervenţie Socială*, *48*, 50–59.

Bryman, A. (2007). Barriers to Integrating Quantitative and Qualitative Research. *Journal of Mixed Methods Research*, *1*(1), 8–22. https://doi.org/10.1177/2345678906290531

Calandro, J. (2007). Considering the utility of Altman's Z-score as a strategic assessment and performance management tool. *Strategy and Leadership*, *35*(5), 37–43. https://doi.org/10.1108/10878570710819206

Cano, M., Matthew, A., Quinn, B., Cano, M., Matthew, A., Quinn, B., Hydraulic, G., Matthew, A. U., Quinn, B., & Cano, M. (2015). *Scotland To cite this version : HAL Id : hal-01149782 Implementing a Greener Hydraulic Fracturing in Scotland*.

Casey et al. (2017). The triple bottom line for efficiency. *IEEE Power & Energy Magazine*, *january/february*, 34–42.

Castro-Alvarez, F., et al. (2018). Sustainability lessons from shale development in the United States for Mexico and other emerging unconventional oil and gas developers. *Renewable and Sustainable Energy Reviews*, *82*(June 2017), 1320–1332. https://doi.org/10.1016/j.rser.2017.08.082

Cokins, G. (2009). *Performance Management* (1 st). Wiley.

Cooper, J., Stamford, L., & Azapagic, A. (2016). Shale Gas: A Review of the Economic, Environmental, and Social Sustainability. In *Energy Technology*.

https://doi.org/10.1002/ente.201500464

Cr, M., & Hafner, M. (2018). *Shale gas production costs : Historical developments and outlook lodie Mistr e*. *20*, 20–25. https://doi.org/10.1016/j.esr.2018.01.001

Creswell, J. W., & Creswell, D. (2018). *Research Design* (Fifth). SAGE Publications.

De Smet, A., et al. (2020). *The need for speed in the post-COVID-19 era — and how to achieve it* (Issue September). https://www.mckinsey.com/~/media/McKinsey/Business Functions/Organization/Our Insights/The need for speed in the post COVID-19 era and how to achieve it/The-need-for-speed-in-the-post-COVID-19-and-how-to-achieve-it.pdf

Derbyshire, J., & Wright, G. (2014). Preparing for the future: Development of an "antifragile" methodology that complements scenario planning by omitting causation. *Technological Forecasting and Social Change*, *82*(1), 215–225. https://doi.org/10.1016/j.techfore.2013.07.001

Editor. (2010). Editor' S Comments : Construct Clarity in Theories of. *Academy of Management Review*, *35*(3), 346–357.

EIA. (2015). *World Shale Resource Assessments*. 2011–2014.

Flage, R., & Aven, T. (2015). Emerging risk - Conceptual definition and a relation to black swan type of events. *Reliability Engineering and System Safety*, *144*, 61–67. https://doi.org/10.1016/j.ress.2015.07.008

Gao, J., & You, F. (2017a). Design and optimization of shale gas energy systems : Overview, research challenges, and future directions. *Computers and Chemical Engineering*, *106*, 699–718. https://doi.org/10.1016/j.compchemeng.2017.01.032

Gao, J., & You, F. (2017b). *Economic and Environmental Life Cycle Optimization of Noncooperative Supply Chains and Product Systems: Modeling Framework, Mixed-Integer Bilevel Fractional Programming Algorithm, and Shale Gas Application*. https://doi.org/10.1021/acssuschemeng.7b00002

Gerring, J. (2017). *Case Study Research* (Second). Cambridge University Press.

Ghasemi, A., & Alizadeh, M. (2017). Evaluating Organizational Antifragility Via Fuzzy

Logic. The case of an Iranian Company. *Operations Research and Decisions*, *27*(2), 21–43. https://doi.org/10.5277/ord170202

Guzman, R. et al. (2018). *Building momentum – oil and gas in Latin America* (p. 16). Arthur D Little. www.adl.com/BuildingMomentum

Hajikazemi, S., Ekambaram, A., Andersen, B., & Zidane, Y. J.-T. (2016). The Black Swan – Knowing the Unknown in Projects. *Procedia - Social and Behavioral Sciences*, *226*(1877), 184–192. https://doi.org/10.1016/j.sbspro.2016.06.178

Hayum, L. (2018). *Latin America month in brief archive*. *December 2017*.

Huimin Tan, Jianhua Xu, G. W.-P. (2019). The politics of Asian fracking: Public risk perceptions towards shale gas development in China. *Energy Research & Social Science*, 2015–2017. https://doi.org/10.1016/j.erss.2019.03.007

IRGC. (2014). *Risk Governance Guidelines Development - Policy Brief*. 1–16.

IRGC. (2017). *Introduction To the IRGC Risk Governance Framework*. irgc.epfl.ch and irgc.org

IRGC. (2018). *Irgc Guidelines for the Governance*. Guidelines for the Governance of Systemic Risks. Lausanne: International Risk Governance Center (IRGC). www.irgc.org

Jackson, S. (2007). A multidisciplinary framework for resilence to disasters and disruptions. *Journal of Integrated Design and Process Science*, *11*(2), 91–108. https://www.scopus.com/inward/record.uri?eid=2-s2.0-62749148341&partnerID=40&md5=b620f5c869c295fd3403ecf8ce49550d

Johnson, J., & Gheorghe, A. V. (2013). Antifragility analysis and measurement framework for systems of systems. *International Journal of Disaster Risk Science*, *4*(4), 159–168. https://doi.org/10.1007/s13753-013-0017-7

Jones, K. H. (2014). Engineering antifragile systems: A change in design philosophy. *Procedia Computer Science*, *32*(Antifragile), 870–875. https://doi.org/10.1016/j.procs.2014.05.504

Kennon, D., Schutte, C. S. L., & Lutters, E. (2015). An alternative view to assessing

antifragility in an organization: A case study in a manufacturing SME. *CIRP Annals - Manufacturing Technology*, *64*(1), 177–180. https://doi.org/10.1016/j.cirp.2015.04.024

Kim, J. H., & Lee, Y. G. (2017). Analyzing the learning path of US shale players by using the learning curve method. *Sustainability (Switzerland)*, *9*(12). https://doi.org/10.3390/su9122232

Koller, D. & H. (2011). *Value - The Four Cornerstones of Corporate Finance*. John Wiley & Sons, Inc.

Le, M. (2018). An assessment of the potential for the development of the shale gas industry in countries outside of North America. *Heliyon*, *November 2017*, e00516. https://doi.org/10.1016/j.heliyon.2018.e00516

Lichtman, M., Vondal, M. T., Clancy, T. C., & Reed, J. H. (2018). Antifragile Communications. *IEEE Systems Journal*, *12*(1), 659–670. https://doi.org/10.1109/JSYST.2016.2517164

Linnenluecke, M. K., & Griffiths, A. (2010). *Corporate sustainability and organizational culture*. *45*, 357–366. https://doi.org/10.1016/j.jwb.2009.08.006

Lunn, S. R. D., Decatur, M. R., Allen, M. L., & Mire, R. A. (2014). One company's upstream water resources management guide. *Society of Petroleum Engineers - SPE International Conference on Health, Safety and Environment 2014: The Journey Continues*, *3*(March), 1585–1595.

Martinetti, A., Chatzimichailidou, M. M., Maida, L., & van Dongen, L. (2019). Safety I–II, resilience and antifragility engineering: a debate explained through an accident occurring on a mobile elevating work platform. *International Journal of Occupational Safety and Ergonomics*, *25*(1), 66–75. https://doi.org/10.1080/10803548.2018.1444724

Matthew Cotton, Ralf Barkemeyer, Barbara Gabriella Renzi, G. N. (2019). Fracking and metaphor: Analysing newspaper discourse in the USA, Australia and the United Kingdom. *Ecological Economics Journal*, *Ext*, *Tel Jorge*, *U*, 2015–2017. https://doi.org/10.1016/j.ecolecon.2019.106426

Mehtha, R. (2020). *PREDICTION OF FINANCIAL DISTRESS USING FINANCIAL PARAMETERS AND ALTMAN Z SCORE WITH JSPM ' S RAJARSHI SHAH U COLLEGE OF ENGINEERING*. *11*, 1–4.

Muerta, V., & Trip, F. (2016). *Vaca Muerta Field Trip December 2016*. *December*.

Mun, J. (2015). *Case Studies in Certified Quantitative Risk Management* (Second). John Wiley & Sons, Inc.

Mun, Johnathan. (2006). *Real Options Analysis* (Second). John Wiley & Sons, Inc.

Passos, D. S., Coelho, H., & Sarti, F. M. (2018). From Resilience to the Design of Antifragility. *PESARO 2018: The Eight International Conference on Performance, Safety, and Robustness in Complex Systems and Applications*, *c*, 7–11.

Platje, J. J. (2015). Efficiency, Fragility, and Unsustainable Development. *Research Papers of Wrocław University of Economics*, *452*, 46–57. https://doi.org/10.15611/pn.2016.452.04

Plattner, T., Plapp, T., & Hebel, B. (2006). Intergrating public risk perception into formal natural hazard risk assessment. *Natural Hazards and Earth System Sciences*, *6*, 471–483. http://www.nat-hazards-earth-syst-sci.net/6/471/2006

Rahm, B. G., Bates, J. T., Bertoia, L. R., Galford, A. E., Yoxtheimer, D. A., & Riha, S. J. (2013). Wastewater management and Marcellus Shale gas development: Trends, drivers, and planning implications. *Journal of Environmental Management*, *120*, 105–113. https://doi.org/10.1016/j.jenvman.2013.02.029

Reed, H., & Meyer, E. (2020). *No Rules Rules - Netflix and the Culture of Reinvention*. Penguin Press.

Rodger, J. A., & George, J. A. (2017). Triple bottom line accounting for optimizing natural gas sustainability: A statistical linear programming fuzzy ILOWA optimized sustainment model approach to reducing supply chain global cybersecurity vulnerability through information and communications t. *Journal of Cleaner Production*, *142*, 1931–1949. https://doi.org/10.1016/j.jclepro.2016.11.089

Ruiz-Martin, C., Lopez-Paredes, A., & Wainer, G. (2018). What we know and do not know about organizational resilience. *International Journal of Production Management and*

Engineering, *6*(1), 11. https://doi.org/10.4995/ijpme.2018.7898

S., H. (2006). Tight Gas Sands. *Journal of Petroleum Technology*, *58*(6), 84–90. https://doi.org/10.2118/103356-JPT

Scrum@Scale en Drummond, (2017). https://scrumcolombia.org/caso-estudio-scrumatscale-drummond/

Seuring, S. (2011). Supply Chain Management for Sustainable. *Business Strategy and the Environment*, *20*(November 2010), 471–484. https://doi.org/10.1002/bse

Sheard, S., & Mostashari, A. (2009). *A Framework for System Resiliance*. *703*, 1–15. http://www.stevens.edu/csr/fileadmin/csr/Publications/Sheard_SystemsResilienceDiscussions.pdf%5Cnpapers3://publication/uuid/4054750A-2BCF-4001-8FB4-4ACF7BCB4C4B

Shortridge, J., Aven, T., & Guikema, S. (2017). Risk assessment under deep uncertainty: A methodological comparison. *Reliability Engineering and System Safety*, *159*(February 2016), 12–23. https://doi.org/10.1016/j.ress.2016.10.017

Son, J. H., Hanif, A., Dhanasekar, A., & Carlson, K. H. (2018). Colorado Water Watch: real-time groundwater monitoring for possible contamination from oil and gas activities. *Environmental Monitoring and Assessment*, *190*(3), 1660–1687. https://doi.org/10.1007/s10661-018-6509-6

Taleb, N. (2012). *Antifragile*. Random House.

Taleb, N N. (2010). *The Black Swan*. Random House.

Taleb, Nassim Nicholas. (2012). Antifragile. In *Antifragile* (pp. 3–27).

Thaler, R., & Sunstein, C. (2009). *Nudge*. Penguin Press.

Thekdi, S., & Aven, T. (2016). An enhanced data-analytic framework for integrating risk management and performance management. *Reliability Engineering and System Safety*, *156*, 277–287. https://doi.org/10.1016/j.ress.2016.07.010

Thekdi, S., & Aven, T. (2019). An integrated perspective for balancing performance and risk. *Reliability Engineering and System Safety*, *190*(October 2018), 106525. https://doi.org/10.1016/j.ress.2019.106525

Tong, X., Zhang, G., Wang, Z., Wen, Z., Tian, Z., Wang, H., Ma, F., & Wu, Y. (2018). Distribution and potential of global oil and gas resources. *Petroleum Exploration and Development*, *45*(4), 779–789. https://doi.org/10.1016/S1876-3804(18)30081-8

Torres, L., Prakash, O., & Khan, E. (2016). Science of the Total Environment A review on risk assessment techniques for hydraulic fracturing water and produced water management implemented in onshore unconventional oil and gas production. *Science of the Total Environment, The*, *539*, 478–493. https://doi.org/10.1016/j.scitotenv.2015.09.030

Torres, L., Prakash, O., & Khan, E. (2017). Chemosphere Holistic risk assessment of surface water contamination due to Pb-210 in oil produced water from the Bakken Shale. *Chemosphere*, *169*, 627–635. https://doi.org/10.1016/j.chemosphere.2016.11.125

Torres, L., Prakash, O., & Khan, E. (2018). Science of the Total Environment Risk assessment of human exposure to Ra-226 in oil produced water from the Bakken Shale. *Science of the Total Environment*, *626*, 867–874. https://doi.org/10.1016/j.scitotenv.2018.01.171

Toseroni, F., Romagnoli, F., & Marincioni, F. (2016). Adapting and Reacting to Measure an Extreme Event: A Methodology to Measure Disaster Community Resilience. *Energy Procedia*, *95*, 491–498. https://doi.org/10.1016/j.egypro.2016.09.074

Trump, B., Florin, M. V., & Linkov, I. (2018). *IRGC resource guide on resilience (vol. 2): Domains of resilience for complex interconnected systems* (Vol. 2). https://doi.org/10.5075/epfl-irgc-262527

Tseitlin, A. (2013). The antifragile organization. *Communications of the ACM*, *56*(8), 40. https://doi.org/10.1145/2492007.2492022

Vargas, C. (2012). Evaluating total Yet-to-Find hydrocarbon volume in Colombia. *Earth Sciences Research Journal*, *16*(Special Issue April), 1–246.

Velandia, C. (2017). *Yacimientos No Convencionales en Colombia - Evolución y Regulación*. Grupo Editorial Ibañez.

WANG, H., MA, F., TONG, X., LIU, Z., ZHANG, X., WU, Z., LI, D., WANG, B., XIE, Y., &

YANG, L. (2016). Assessment of global unconventional oil and gas resources. *Petroleum Exploration and Development*, *43*(6), 925–940. https://doi.org/10.1016/S1876-3804(16)30111-2

Wang, K., Vredenburg, H., Wang, T., & Feng, L. (2019). Financial return and energy return on investment analysis of oil sands, shale oil and shale gas operations. *Journal of Cleaner Production*, *223*, 826–836. https://doi.org/10.1016/j.jclepro.2019.03.039

Williams, P. R. D. (2015). Applying risk analysis to two divisive topics: Hydraulic fracking and marijuana use. *Risk Analysis*, *35*(5), 762–765. https://doi.org/10.1111/risa.12420

Winston, A. (2017). The Big Pivot. In *The Big Pivot Chapter 14*. Harvard Business Review Press.

Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering and System Safety*, *141*(April 2015), 5–9. https://doi.org/10.1016/j.ress.2015.03.018

Yang, Y., Wang, L., Fang, Y., & Mou, C. (2017). Integrated value of shale gas development : A comparative analysis in the United States and China. *Renewable and Sustainable Energy Reviews*, *76*(November 2016), 1465–1478. https://doi.org/10.1016/j.rser.2016.11.174

Yin, R. K. (2018). *Case Study Research and Applications* (Sixth). SAGE Publications.

Zerda, M. A. D. La, Erdmann, E., Tecnológico, I., Aires, D. B., Sarandón, R., & De, U. N. (2017). *SPE-185546-MS Importance of the Study of Environmental Aspects in the Exploitation of Unconventional Reservoirs for Risk Assessment of the Activity in Argentina*.

Zio, E. (2018). The future of risk assessment. *Reliability Engineering and System Safety*, *177*(April), 176–190. https://doi.org/10.1016/j.ress.2018.04.020

Zuluaga Guerra, A. D., & Monterroza Villalba, R. I. (2019). Licencia social como mecanismo de desarrollo de yacimientos de hidrocarburos no convencionales en el departamento del Cesar-Colombia. *Revista Fuentes El Reventón Energético*, *17*(2), 101–110. https://doi.org/10.18273/revfue.v17n2-2019009

Appendix A

Definitions

Antifragile Organization: is able to not only survive but also to prosper or thrive in turbulent environments.

Black Swan: an event meeting three criteria 1) It is an outlier as it lies outside the realm of regular expectations; 2) It carries extreme impact; and 3) Human nature makes us concoct explanations for its occurrence after the fact, making it seem explainable and predictable.

EBITDA: net income (or earnings) with interest, taxes, depreciation and amortization added back. It can be used to analyze and compare profitability among companies and industries, eliminating the effects of financing and capital expenditures.

Fragile Organization: is not able to withstand changing environments: it collapses.

Gross margin: a company's net sales revenue minus the cost of goods sold (COGS). In other words, it is the sales revenue a company retains after incurring the direct costs associated with producing the goods it sells and the services it provides. The higher the gross margin, the more capital a company retains on each dollar of sales, which it can then use to pay other costs or satisfy debt obligations. The net sales figure merely is gross revenue, less the returns, allowances, and discounts.

Organizational Resilience: the measurable combination of characteristics, abilities, capacities, or capabilities that allows an organization to withstand known and unknown disturbances and survive.

Performance Antifragility: the ability to improve performance relative to the performance Reference Level over time following a sequence of changes in condition or events (known or unknown type of changes or events).

Performance Competitive Advantage: the ability to be in a superior operating position due to high levels of Performance Resilience and or Performance Antifragility.

Performance Resilience: the ability to regain/restore the performance Reference Level following a change in condition or event (known or unknown type of change or event).

Performance-risk: deviation in performance relative to a reference level and associated uncertainties. Future performance is generally described by the triplet (O, Q, K), where O is a specified system output. Q is a measure of uncertainty associated with O, and K is the background knowledge that supports O and Q.

Resilient Organization: is not only robust, but it is also able to survive unforeseen events.

Robust Organization: can survive some set of changes in the environment. However, if these changes are outside the designed parameters, the organization will probably collapse.

ROCE: Return on capital employed is a financial ratio used to assess a company's profitability and capital efficiency. In other words, the ratio can help to understand how well a company is generating profits from its capital.

ROIC: Return on invested capital is a calculation used to assess a company's efficiency at allocating the capital under its control to profitable investments. The return on invested capital ratio gives a sense of how well a company uses its money to generate returns.

TSR: Total shareholder return is the internal rate of return (IRR) of all cash flows to an investor during the holding period. Whichever way it is calculated, TSR means the same

thing: the total amount returned to investors, including capital gains and dividends, when measuring the total return generated by stock to an investor.

Appendix B

Customarily Metrics in the Oil and Gas industry and UOG

1) Financial
    i. Liquidity
        1. Strip 2020/2021 total payout ratios
        2. Current net debt/total cap metrics vs. targeted ceilings and historical peaks
        3. Funding of near-term debt maturities
        4. Liquidity positions
        5. Excess Cash Ratio
    ii. Cash Flow
        1. Operational cash flow generation (OCF)
        2. Free cash flow generation (FCF) = OCF - Investments (before Dividends and Buybacks)
        3. Cash Flow per Share (CPFS) Y/Y Growth
        4. Cash Flow from Financing (CFFF)
    iii. Financial distress
        1. Net Debt/EBITDA; should be > 4.0
        2. Net Debt/adjusted EBITDAX
        3. Net Debt/Capital
        4. Payout (Post DRIP)
        5. Debt rating
    iv. Recycle Ratio: Profit (netback: revenues – all costs including royalties, transportation, and production costs) per BOE/Cost of finding and development BOE; should be > 1.0

v. Quarterly results
vi. Financial ratios
    1. Altman’s Z-Score
    2. Tobin's q

2) Operational
    i. Output
        1. Oil and gas production (MBOED)
        2. Production Y/Y Growth (% CAGR)
        3. Reserves incorporation (MMBOE/year)
    ii. Efficiency
        1. Breakeven price (USD/BOE)
        2. First-month oil production per new well (BOE/well)
        3. EUR per well (BOE/well) and BOE/ft
        4. New-well oil production per rig (BOE/rig)
        5. Average cost per unit of IP (USD/production (180 days))
        6. Development cost (CAPEX/BOE)
        7. Operational cost (OPEX/BOE)
    iii. Drilling and Completion efficiency
        1. Oil production/rig (bbl/day)
        2. Gas production/rig (Mcf/day)
        3. Hours/stage Completion
        4. Lateral length/well (foot)
        5. Stages/well
        6. Pounds Proppant/stage
        7. MM Pounds/stage/hour
        8. Drilling days/1K lateral feet
        9. Proppant Load (pounds)/Lateral foot
        10. Weighted Average Days (Completion/Drilling)/well
        11. Weighted average MM lbs. of Water & Proppant Pumped per day

3) Avoid HSE and integrity incidents
    i. FAR: Fatal Accident Rate
    ii. LTIF: Lost Time Injury Frequency
    iii. TRIR: Total Recordable Injury Rate
    iv. PSIF: Process Safety Frequency Index

v. Disruptive event: Ratio of Recovery and Loss

4) Value creation
   i. Global, Independent, and National Oil Companies
      1. ROCE: return on capital employed
      2. ROIC: return on invested capital
      3. Profitability Index: 1 + NPV10/discounted capital employed
      4. 5-year Return (%)
      5. Dividend Yield (%)
      6. Enterprise Value (EV)
      7. Market Capitalization (MC)
      8. Enterprise Value/Market Capitalization
   ii. New ventures (Subsidiaries and Joint ventures)
      1. Production growth (BOE/year)
      2. Time to commit development (years)
      3. Investment/acreage ratio
      4. Project execution: Time, Cost, Quality
   iii. Expected Cash Flows
      1. Net Present Value (NPV)
      2. Enterprise Value/Net Present Value

5) Environmental
   i. Energy use
      1. Energy return on investment
      2. Total energy use (millions Gj)
      3. Energy intensity (Gj/m3)
   ii. Emission intensity
      1. Greenhouse Gas Emissions (GHG) Intensity Rate (tCO2e/mboe): CO2, CH4, N_20, NOx, SOx, VOC.
      2. Carbon emission per year (tCO2/year)
      3. A breakdown of emissions by source (Flaring, Venting, Fugitives, Combustion) (Mcf/day) per Mbo/day of gross oil production
      4. ESG Proprietary Indexes
         a. Upstream oil and gas carbon risk index (Verisk Maplecroft).
         b. Sustainability Overall Score (Sustainalytics).
         c. ISS (MSCI)
   iii. Water Usage

1. WUNFS: Percentage of water use from fresh and non-freshwater sources.
2. Freshwater Intensity (bbl/BOE)
3. Water Reuse Percentage.

iv. Land use
1. Footprint of activity (Hectares)
2. Spill incident rate (number of spills/MMBOE)
3. Volumes spilled/MMBOE production
4. Pipeline incident/1,000 km

v. Executive Annual Bonus Goals Include ESG Performance

6) Social Sustainability
i. Employment
1. Direct employment (person-years)
2. Local employment (%)

ii. Nuisance
1. Noise (dB)
2. Traffic (%)
3. Earthquakes (Number over threshold/year)

iii. Public perceptions
1. Public support (%)
2. Media impact

iv. Local communities
1. Spending on local or domestic suppliers (%)
2. Direct community investment (%)

7) Governance
i. Equity of distribution of benefits and costs
ii. Information and monitory capacity
iii. Accountability
iv. Polycentric governance
v. Democratic inclusiveness
vi. Dispute resolution
vii. Adaptability and flexibility