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Review

Measuring Supply Network Resilience Using a Mixed Approach (Case Study: Oil and Gas Companies)

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ABSTRACT

Today, random and intelligent risks have made supply management disruptive much more than before. Over the past decade, many supply network (SN) disruptions in oil and gas industry have been due to the deliberate risks posed by international sanctions. Undoubtedly, resilience in general and resilience of SN in particular has been a systematic method for firms and organizations to deal with disruptions. This study aimed to measure, assess, and compare the resilience of SNs in oil and gas companies based on a mixed approach of systematic literature review (SLR) and complex adaptive systems (CAS). The statistical population of the study consisted of 11 subsidiaries of the National Iranian Oil Company. A robust systematic review of the literature was conducted to collect all the crucial components of supply network resilience (SNR) from 608 articles that ultimately resulted in 40 key factors based on the context intervention mechanism outcome logic (CIMO-logic). Quantitative analysis was carried out in the upstream sector of three subsidiaries of Iranian Central Oil Fields Company (ICOFC) including South Zagros, East and West Oil and Gas Production Companies. The results demonstrated a relationship between components and their measurement in upstream companies. A further finding is that South Zagros Oil and Gas Production Company was more resilient than the other two companies.

1. Introduction

Under normal circumstances, economic conditions of a country are considered to be sound in terms of macroeconomic variables such as inflation, employment, or unemployment; however, when facing internal and external risks like environmental changes, economic and political structures and global business conditions would be affected. This particularly matters for oil and gas industry, so the price fluctuations of oil importing and

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exporting countries may have considerable consequences on its activities.

Concentrating on the experience of the countries and successful organizations during the past decade has shown that they could handle vulnerabilities resulting from oil price fluctuations through incorporating such policies as stakeholder engagement, creating a logistics hub in oil exporting countries, risk sharing in supply chain (SC) partnerships, building strategic reserves, reducing dependence on fossil fuels, and forming multilateral coalitions. Obviously, in the case of Iran as an oil exporting country, one of the most effective ways to improve supply management is to reduce vulnerability and increase the resilience especially in the upstream sector of the oil industry.

It is obvious that businesses cannot work as separate and independent entities in a competitive environment, but can operate and compete in the framework of network (Min and Zhou, 2002). The result of recent developments in SC theory is the emergence of supply network (SN). SNs are crucial components of competitive and globalized markets (Rezapour et al., 2018). The more the community depends on network, the more the network is doomed to failure. Conversely, because SNs are globally distributed, they are vulnerable to risks in business (Rezapour et al., 2018). While companies must address disruptions in the SC as realistic possibilities, most SC models fail to capture them sufficiently (Schmitt and Singh, 2012). Although many studies addressed the possibility of disruption in SC focused on single facilities or pairs of echelons in a SC, disruptions can bring about long-lasting effects throughout the SC (Schmitt and Singh, 2012).

There is ample evidence that the growth of disruptions, especially catastrophic events during the last decade such as September 11 terrorist attacks, Japan earthquake and tsunami and its subsequent nuclear disasters, Typhoon Haiyan, and Hurricane Katrina, is increasing throughout the world. It seems that organizations are unable to predict the outcomes, decisions, and the effect of disruptions on their future SCs. Moreover, decision makers may face risk management due to misjudgment or miscalculation in assessing the risks or understanding the complexity of risks or unpredictability of disruptions and sometimes individual management approaches (Kwesi-Bour, 2015).

Brusset and Teller (2017) defined supply chain resilience (SCR) as an operational capability that enables a disrupted or broken SC to rebuild itself and be stronger than before.

According to their work, the literature on supply chain management has explored how to build SCR with increasing attention especially toward the fragmentation of value chains (Brusset and Teller, 2017). This leads to the growth of resilient networks against the growing trend of failures.

In recent years, there has been an increasing interest in the evolution of supply network resilience (SNR) in the oil and gas industry. Moreover, the challenges in the upstream oil and gas industry, on the one hand, and the supply of goods or services in the current economic situation of the country, on the other hand, can illustrate the dominant role of resilience in supply network management.

One of the very important and basic infrastructures in the process of urban and rural life development in Iran over the past few years is the role and position of the production companies on the country's oil and gas supply. The significance of the production companies will be maximized when the SN in the oil and gas industry faces disruption or interruption due to the sanctions and unexpected events that may lead to irreparable damage. Given adopting the preventive approach throughout the country despite the spread of Post-JCPOA[1] events, unexpected accidents, and damage caused by natural disasters like flood, earthquake, etc., the supply and distribution of oil and gas throughout the country appears stable, which results from taking resilience measures. This implies that resilience is associated with the abilities of systems to cope with the threats, disasters, and severe disruptions with minimal damage to the economic, social, and environmental infrastructures and to recover as quickly as possible.

It is worth noting that the economy of our country is hugely based on oil revenues. Therefore, there is no doubt that improving the resilience of the oil and gas industry will thus contribute to the long-term resilience of economic development. Hence, managing oil revenues help to develop resilient and sustainable firms and organizations.

2. Background

2.1. Supply Chain and Supply Network

Although the focus of supply chain management approaches is on the unit of analysis, i.e. network or

[1] Joint Comprehensive Plan of Action

chain, a few studies have examined the similarities and differences of the importance of the two concepts of chain and network. Pettit et al. (2010) introduced the SC as a network of organizations involved in the flow of goods, services, finance, and information about the primary supplier to the final customer (Chowdhury, 2014). Therefore, the SC no longer exists as a separate entity (Lambert and Cooper, 2000), but it is interdependent in the form of dynamic networks (Hakanssom and Snehota, 1989) or is a system of entities the purpose of which is to create a tunnel for three flows: information, raw materials/products, and finance (Mean and Zhou, 2002, p. 233). Thus, the SN is the combination of transport companies, retailers, distributors, suppliers, and infrastructure logistics, which aim to promote the production, delivery, products, and services through working with together.

By conceptualizing the SC, it can be considered as a set of several SCs in which not only the indirect relationships of affiliated organizations but also the direct relationships between the members are formulated. The dynamic SC is based on mutual trust and complex and nonlinear relationships. The integrity of SN is often special, temporary, and unplanned. Therefore, SC operations may be less predictable, so integration in SNs requires comprehensive information management (Uzzi, 1997; Hakanssom and Snehota, 2000; Ritter et al., 2004; Choi and Krause, 2006). A few studies have been conducted in the area of SNs. Some researchers like Mizgier et al. (2015) claim that most of the studies have focused on the relationship between supplier and buyer, rather than the structure of networks.

2.2. Resilience in Supply Chain/Supply Network

SCR as a relatively new concept originating from a broader concept of resilience is derived from risk management in SC and represents a combination of supply chain management and risk management (Chowdhury, 2014).

Research on resilience has proliferated in recent years. Numerous definitions, tactics, metrics, and indices have been proposed. However, most of them are formulations with little or no formalized theoretical underpinnings. A comprehensive framework for the analysis of how enterprises or firms cope with disasters is still lacking (Dormady et al., 2018).

The literature on hazards and vulnerability shows that there are three definitions of resilience. The first group extends resilience to one side and vulnerability to the other end of the spectrum (Adger et al., 2005; Brikmann, 2006; Cannon, 2007). The second group believes in high independence and to some extent in the overlap of the two concepts, namely resilience and vulnerability (Buckle et al., 2001; Gallopin, 2006; Timmermann, 1981; Turner et al., 2003). The third group believes in the overlap of the two concepts (Cutter et al., 2008). According to the work of Gallopin, while vulnerability is defined as the capacity to maintain the structure of a system, resilience is defined as the capacity to recover the system from unstructured changes in a dynamic environment. In other words, vulnerability refers to the baseline and initial state, while resilience indicates the ability of the system to fluctuate (Sudmeier-Rieux and Switzerland, 2014, p. 71).

If SC risk management pays particular attention to the identification and management of risks, the goal of supply chain is to develop adaptability to encounter the unexpected events and improve them after disruptions (Chowdhury, 2014). The overarching concept of resilient SC was introduced by Ponomarov and Holcomb (2009): Resilience is adaptability in the face of unexpected events, response to disruptions, and post-disaster recovery, recovery through business continuity at an optimal level, and control over structure and performance (Ponomarov and Holcomb, 2009, p. 131). As Sheffi and Rice (2005) stated SCR responds to disruptions of three distinct stages: readiness, responsiveness, and recovery. Moreover, the response of the system and the time of recovery have also been considered in many studies as resilience indicators, implying that these concepts are interrelated and cannot be considered separately. Therefore, SCR includes the indicators of capability, design, preparation, response, and recovery (Chowdhury, 2014). SCR is also a precise measure to assure SC is in good condition (Pettit et al., 2010). Compared to traditional SCs that basically focus on risk control, SCR emphasizes the compatibility, flexibility, and recovery from SC disruptions based on the fact that all disruptions are not avoidable (Pettit et al., 2013). By examining the SC/network studies and relying on distinguished and highly cited works on the operations management, as illustrated in Figure 1, supply resilience has progressed from its traditional definitions and primary concepts to the measurement and assessment of the components of resilience and supplier selection.

In this study, the resilience concept is replaced with resistance, namely the ability to return to the normal pre-disruption condition. Dealing with the constant environmental uncertainties, the SCs and SNs must be flexible and adaptable, especially in the face of normal and abnormal disruptions that are complex and permanent.

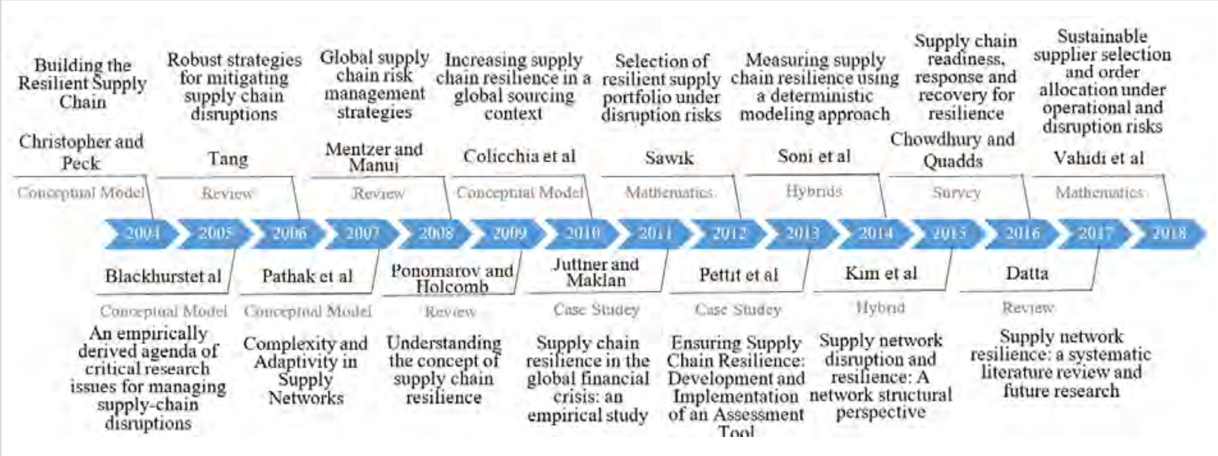


Figure 1. Highly cited works in the field of supply chain/network resilience from 2001 to 2018.

2.3. Theoretical Background of SCR

The issues related to the design of resilient SC are generally classified under three categories: (1) the design of resilient SC (Klibi et al., 2008; Canbolat et al., 2007), (2) the assessment of the resilience of SC caused by disruption (Klibi and Martel, 2012; Solo, 2009; Manikandan, 2008), and (3) the development of SCR (Harrison et al., 2013; Klibi and Martel, 2012; Schmitt and Singh, 2009). Studies on SCR are classified under three groups (Kungwalsong, 2013), including conceptual frameworks (Xiaoyan and Xiaofei, 2012; Asbjornslett, 2009) empirical studies (Wagner and Neshat, 2010), and analytical models (Chowdhury and Singh, 2012). Furthermore, the following are approaches to recovering and improving SCR over the past decade:

- Scenario-based modeling approach (Klibi and Martel, 2012);
- Simulation approach to quantifying the risk in the SC (Schmitt and Singh, 2009);
- Mathematical modeling approach to developing decision support systems to reduce disruptions (Snediker, 2008);
- Optimization approach to improv the resilience (Kungwalsong, 2013).

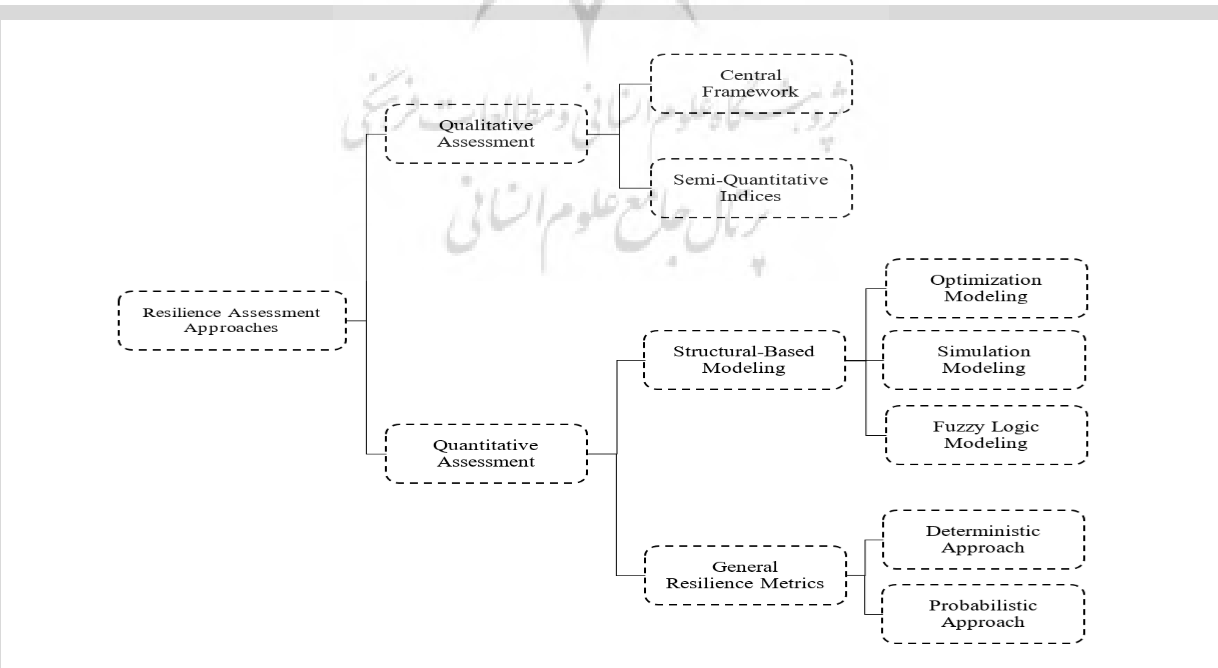


Figure 2. Classification scheme of resilience assessment methodologies (Hosseini and Barker 2016, p. 27).

Little attention has been paid to developing SNR models, and a few researchers have addressed the issue. Hosseini et al. (2019) suggested an efficient solution to the resilient supplier selection and optimal order allocation problem. Dormady et al. (2018) provided a microeconomic foundation for analyzing a comprehensive range of these tactics, incorporating both inherent and adaptive concepts of resilience. Ledwoch et al. (2018) proposed an agent-based model to explore the relationship between topological characteristics of complex SNs and their ability to recover through inventory mitigation and contingent rerouting. Li (2017) published three essays, namely "value of supply disruption information and information accuracy", "quantifying supply chain resilience: a dynamic approach", and "network characteristics and supply chain disruption resilience," studying three closely related aspects of SCR. Hosseini and Barker (2016) proposed a Bayesian network (BN), which is a paradigm that effectively models the causal relationships between variables but has not been used in the context of supplier evaluation and selection, to quantify the appropriateness of suppliers across primary, green, and resilience criteria. Mari et al. (2015) developed different resilience metrics for SCs based on a complex network theory and then used a resilient SC growth algorithm for designing a resilient SC. Mizgier et al. (2015) proposed a model for the quantification of business disruption risk in a global SC. They indicated that diversification effects can lead to counterintuitive results when we consider the network structure and the correlations of hazard events. Their findings demonstrated more informed and crucial decisions for SC design. Levalle and Nof (2015) stated that resilience by teaming (RBT) association decisions, inspired in the fault-tolerance by teaming principle from collaborative control theory, are characterized and applied to network formation and reconfiguration mechanisms. Tipper (2013) highlighted the complexity and challenges of providing reliable services in the evolving communications infrastructure. Sawik (2013) dealt with the optimal selection and protection of part suppliers and order quantity allocation in a SC with disruption risk. Braziotis et al. (2013) made an outline classification of relevant dimensions where the concepts of SC and SN are compared and their distinctive features are highlighted. Klibi and Martel (2012) studied various modeling approaches to designing resilient SNs for the location–transportation problem under uncertainty. The future environment of the SN is shaped by random demands and by disruptions perturbing depots capacity and ship-to-point demand processes. Also, Carvalho et al. (2011) proposed a model that could be the basis for further research in lean, agile, resilient, and green paradigms, contributing to a more sustainable and competitive lean SC with the necessary agility toward a quick response, resilience to disruptions, and harmonization with the ecologic and environmental aspects.

3. Methodology

3.1. SLR Based on CIMO-Logic

SLR was used in the first phase of the data analysis. As noted in the theoretical background of the approach, the SLR approach has emerged in the field of medical science, and, unlike the narrative review approach, aims to systematically review the elimination of deviation and improve the quality of the review process through guaranteed accuracy, reproducibility, and access to relevant research (Kochan, 2015). The SLR is based on the four key principles of methodology, namely transparency, inclusiveness, heuristics, and innovation. Based on these four principles, the five steps of the SLR approach are as follows (see Figure 3): (1) framing the question; (2) identifying the relevant work; (3) assessing the quality of studies; (4) summarizing the evidence (data synthesis); and (5) interpreting the findings (Kochan, 2015).

a. Framing research question

A question in the SLR approach can be separated and subdivided into further questions. We can adopt the CIMO-logic to accomplish this. The questions of context characterize the subjects, rules, or the systems of the study. The questions of intervention determine the effects of an event, action, or activity. The questions of mechanism are used as a medium between tools and methods used for outcomes. Finally, the questions of outcome determine the effects of the disruption and the outcome measures.

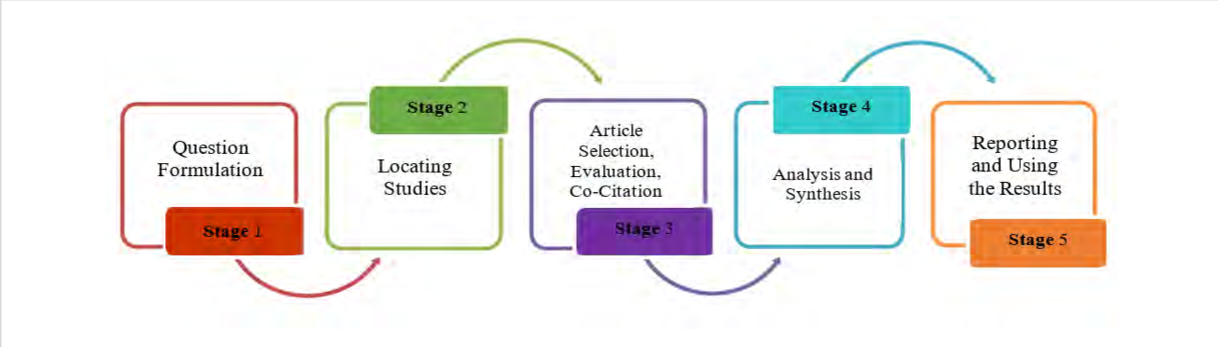


Figure 3. SLR methodology.

b. Identifying relevant work

By reviewing the theoretical background of SNR, 608 papers were collected using the HistCite program. Collecting data was based on keywords such as network, SC, SC risks, network disruption, network vulnerability, SC, network resilience that were used in papers published from 2001 to 2018. Web of Science was utilized as a regular index database to find articles from online databases including Emerald, Oxford, ScienceDirect, Springer, Francis Taylor, and John Wiley.

Table 1. Summary of selection criteria from 2001 to 2019.

Acceptance Criteria	Emerald	Oxford	Science direct	Springer	Francis Taylor	John Wiley	Etc.	Total
Supply Chain/Network Supply Chain/Network; Disruption Supply Chain/Network; Disruption; Risk Supply Chain/Network; Disruption; Risk; Resilience	126	46	163	33	108	73	59	608

c. Assessing the quality of studies

The 18-year interval between 2001 and 2019 was the starting point of this study due to the early research on the SCR. More than 608 papers were collected in the first phase.

Two approaches were employed for assessing the articles. The first approach was based on the thematic evaluation of the paper and the related journal in which the paper was published. Thus, based on the relevance and irrelevance of the title, the abstract, and the overall content of the article, on the one hand, and journal evaluation indicators (including impact factor, SJR, Quartile ranking, and H-index), on the other hand, the papers relevant to the research topic have been selected and assessed. Table 2 summarizes the screening results of the articles in the first phase of assessment. At this stage, 260 papers are selected from the 608 original articles.

The second approach to selecting and assessing the appropriate articles was based on the critical appraisal skills program (CASP), which is an effective method for assessing articles in meta-research methods, including meta-analysis and meta-synthesis. Based on the ten criteria of the CASP, a score is assigned to each article. The ten criteria of the CASP include clear statement of the aims of the research, quality of research method, research design and strategy, data collection, methods of communication between researchers and participants, ethical principles, rigor of the study, qualitative research findings, and research value. Finally, out of 260 articles of the previous stage, 215 paper were approved. Table 3 presents the samples used this approach.

Table 2. The 260 articles collected in the second phase.

Acceptance Criteria	Emerald	Oxford	Science direct	Springer	Francis Taylor	John Wiley	Etc.	Total
Supply Chain/Network; Disruption; Risk; Resilience	126	46	163	33	108	73	59	608
Filter Articles: "Title"	86	46	123	26	78	58	49	456
Filter Articles: "Abstract"	71	36	108	21	63	43	42	379
Filter Articles: "Context"	65	31	102	20	57	37	36	337
Filter Articles: "Journal Evaluation Indicators[1]"	54	20	91	9	46	26	25	260

Table 3. Evaluation of articles based on CASP approach.

	CASP Criteria / Article Title	Clear statement of the aims of the research	Methodology appropriate	Research design appropriate	Sampling	Data collected	Relationship between researcher and researcher	Data analysis sufficiently rigorous	Clear statement of findings	Research Value	Ethical issues	Total
1	Measuring SCR using a deterministic modeling approach	5	5	4	5	5	4	4	5	4	4	45
2	Resilient supplier selection and order allocation under operational and disruption risks	5	5	4	4	4	4	5	4	5	4	44
…	…	…	…	…	…	…	…	…	…	…	…	…
12	Toward a resilient holistic SC system: concept, review, and future direction	4	4	5	4	4	4	4	4	4	4	41
…	…	…	…	…	…	…	…	…	…	…	…	…
50	Selection of risk mitigation strategy in electronic SCs using grey theory and digraph-matrix approaches	4	4	3	4	4	3	3	4	3	4	36
…	…	…	…	…	…	…	…	…	…	…	…	…

The rationale for selecting the articles is that each of the ten criteria is rated by scoring each item from poor (1) to excellent (5). Therefore, the papers are then classified under five categories: Excellent (41 to 50); Very Good (31 to 40); Good (21 to 30); Moderate (11 to 21); and Poor (zero to 10). Subsequently, based on the accepted articles, which included Excellent, Very Good, Good, and Moderate articles, a total of 215 articles out of 260 were peer-reviewed.

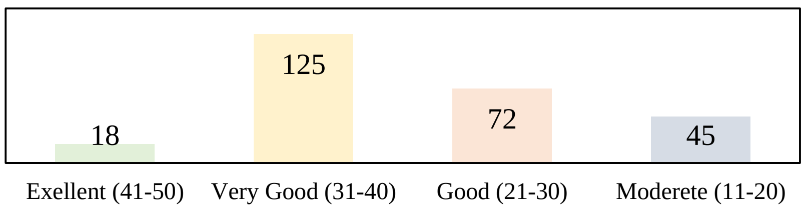


Figure 4. The final articles selected by the CASP approach.

[1] H-Index; JJR; Impact Factor; Q1

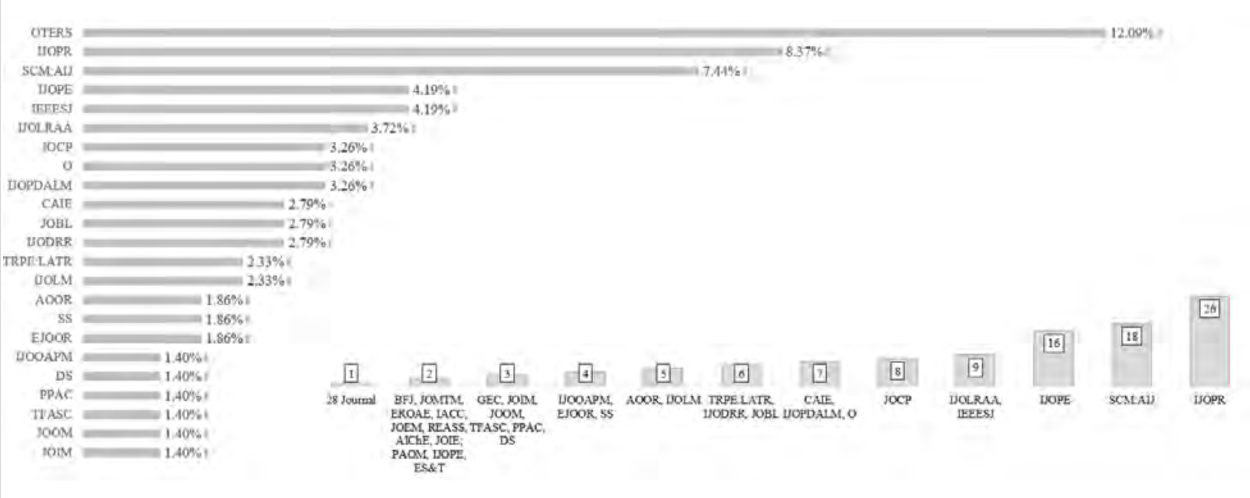


Figure 5. Frequency of the 215 articles based on the CASP assessment.

The SLR refers to a method for reviewing and assessing articles qualitatively or quantitatively. Investigating the quantitative and qualitative approaches of the present research indicates that the majority of the studies are case studies (24%). The other works are mathematical planning (14%), review studies (13%), and conceptual modeling (12%). In addition, simulation methods, quantitative–qualitative, surveying, modeling, and multi-criteria decision-making methods respectively cover 11, 10, 9, 6, and 2% of the studies.

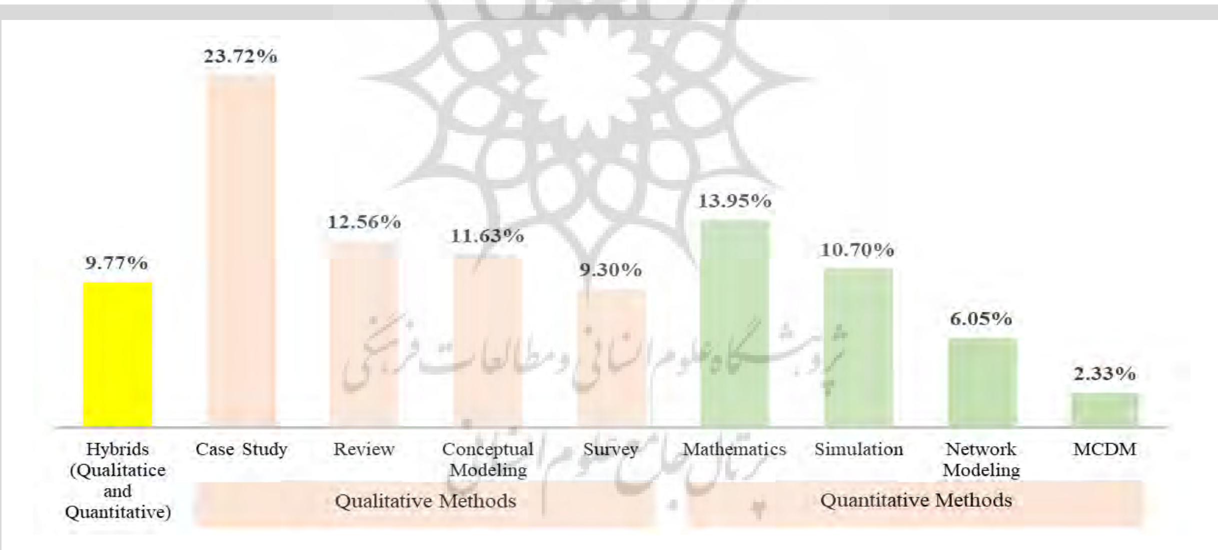


Figure 6. SLR mechanisms: the quantitative and qualitative methods of the selected articles.

Furthermore, the trend of reviewing the articles in recent years shows preference for qualitative over quantitative approaches. Examining 84 articles out of the 215 articles in the past three years, i.e. from 2016 to 2018, demonstrates that case studies, surveys, quantitative–qualitative studies are ranked with the highest frequency compared to the other methods respectively (see Figure 7).

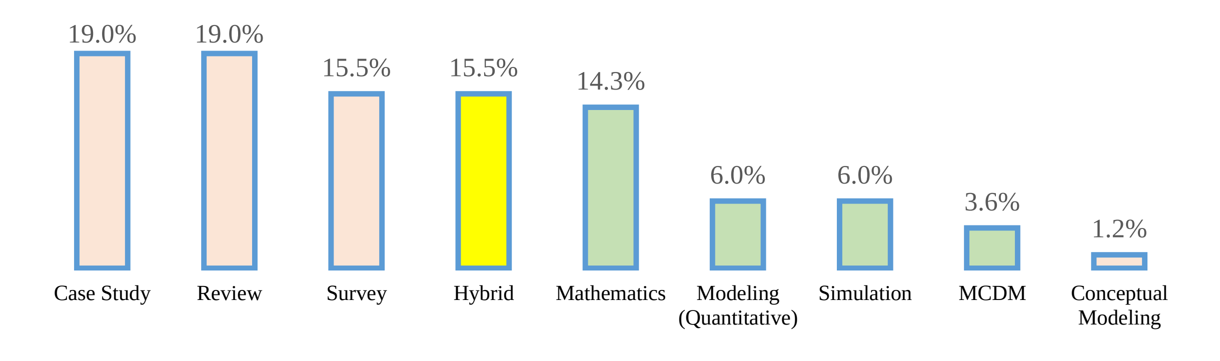


Figure 7. SLR mechanisms (2016–2018).

d. Summarizing the evidence (data synthesis)

As the presented framework (see Table 2) is based on the frequency of keywords, disruption, vulnerability, and capability were considered to be the keywords in the context of the articles. Also, vocabularies of reactive and proactive strategies within the interventions, and quantitative research methods, i.e. mathematical modeling, mathematical planning, simulation, multi-criteria decision making, and hybrid studies, and qualitative research methods, i.e. case study, conceptual modeling, review article, and survey, were developed as mechanisms in the CIMO-logic. Furthermore, the outcomes of resilience fell into three groups: adaptation through readiness, response through accountability, and recovery and improvement.

Context	Interventions	Mechanisms	Outcomes
Disruptions: Natural disasters; Sanctions; Lack of integration; Unpredictability; Inventory rate; Bullwhip effect; Inefficient analysis; Lack of information; Low quality **Vulnerabilities:** Exchange rate fluctuations; Prices of raw materials; Downturn; Lack of funds; Contacting the supplier; Lack of vital goods **Capabilities:** Information sharing; Efficient staff; Contract flexibility; Production flexibility; Alternative capacity; Safety stock; Resource Optimization	**Reactive Strategies:** Use of information Technology; Contingency planning; Support creation; Partnering with supply partners; Create redundancy; Demand management; Supply Agility Measurement **Proactive Strategies:** Design Robust supply structure; Create support capabilities; Establish appropriate agreements; Partnering with the government; Portfolio diversification; Supplier Selection; Inventory management	**Qualitative:** Case Study; Conceptual Modeling; Review; Survey **Quantitative:** Modeling; Mathematics; Simulation; MCDM **Hybrids:** Quantitative–qualitative; Qualitative–quantitative	**Readiness** For disruption **Response** To the disruption **Recovery** After disruption **Learning** After the disruption

Figure 8. The typology of the SNR based on the CIMO-logic.

e. Interpreting the findings

The final step is to present the findings. Although there is a large number of articles in the area of SC management such as SC risk (Pereira et al., 2014), the frequency of articles in the new field of the SNR is very low (Hohenstein et al., 2015). Table 4 lists the classification and analysis of the papers. Based on the SLR approach, the assessment of the articles falls into three categories: journal description (year and publication), methodology (article type), and article configuration based on the CIMO classification approach (Kochan, 2015).

Table 4. Classification and analysis of the articles.

Area	Category	Information
Descriptive	Year	Publication year
	Journal	Name of the peer-reviewed journal in which the article was published.
	Title	Full title of the article
Methodology	Article type	Classification of articles consists of two main categories: quantitative and qualitative.
Configuration articles	Context	Thematic classification of articles based on keywords: disruptions, vulnerability, and capabilities
	Interventions	Classification of resilient SN drives and agents, including reactive resilience and proactive resilience
	Mechanisms	Quantitative: modeling, mathematical programming; simulation; multi-criteria decision making; hybrids; Qualitative: case study; conceptual modeling; review; and survey
	Outcomes	Readiness for disruption; response to the disrupt; recovery after disruption; and learning after the disruption.

Studying the findings of the SLR approach under the CIMO-logic shows that among the factors and variables influencing the resilience of the SN, the majority of the researches are associated with the following variables.

- Disruption variables, including disruptions of demand, supply, infrastructure, lead-time, and transportation.
- Vulnerability variables, including terrorism components, natural disasters, financial crises, lack of access to labor, demand–supply imbalance, political challenges, lack of required skills, lack of planning, and control.
- Capability variables, including communication components, accessibility, collaboration, learning, technological innovation, flexibility, multi-resource, redundancy, leadership, and knowledge management.

Like the contextual variables, the study of intervention variables also shows that researchers identify agility, collaboration, flexibility, visibility, knowledge management, integration, adaptability and compatibility, and the sustainable SC as a subset of reactive resilience strategies. On the other hand, they consider robustness, collaboration, redundancy, forecasting, knowledge management, infrastructure, robust SC, and the SN complexity as a subset of proactive resilience strategies.

Finally, surveying the outcome variables also indicates that most of the studies focus on the three main types of resilience:

- Resilience is change-ready and adapts well to changes.
- Resilience is responding well to changes and is change-responsible.
- Resilience is recovery to their original state and improvement.

What is important is that the first type refers directly to the proactive resilience approach, while the third addresses the reactive resilience approach. However, the second type refers to both approaches. Therefore, the above approach can be examined from both preventive and reactive strategies aspects. Hence, the dimensions and components of the SNR based on the CIMO-logic are mentioned in Table 5.

Table 5. Specifications of the SNR model.

Dimensions	Components	Index	Description and some resources
Disruptions	Natural disasters	R_{11}	Including earthquake, flood, and … (Christopher and Peck, 2004; Sheffi and Rice, 2005; Kleindorfer and Saad 2005)
	Sanctions	R_{12}	Regional and international sanctions (Blos et al., 2009; Xu, 2008)
	Lack of integration	R_{13}	Lack of integrity in access to information (Gaudenzi and Borghesi, 2006)
	Unpredictability	R_{14}	Inaccuracies in forecasting (Pettit et al., 2013; Sheffi, 2005; Blauckhurst et al., 2005)
	Inventory rate	R_{15}	Excess inventory or inventory shortages (Pettit et al., 2013)
	Piracy and theft	R_{16}	Includes copying, storage, sale or other use of intellectual property (IP) protected by copyright law (Pettit et al., 2010; Sheffi, 2005)
	Industrial espionage	R_{17}	Spying directed toward discovering the secrets of a rival manufacturer or other industrial company (Pettit et al., 2010)
	Price pressures	R_{18}	Price pressures from unhealthy competition (Pettit et al., 2010)
	Exchange rate fluctuations	R_{19}	Exchange rate fluctuations and multipliers (Manuj and Mentzer, 2008)
Vulnerabilities	Low quality	R_{21}	Poor quality of raw materials (Pettit et al., 2010)
	Prices of raw materials	R_{22}	Raw material price fluctuations (Blos et al., 2009; Xu, 2008)
	Downturn	R_{23}	Economic turmoil, especially unemployment (Blos et al., 2009)
	Lack of funds	R_{24}	Lack of funds and high bank interest rates (Blos et al., 2009; Xu, 2008; Tang, 2006)
	Contacting the supplier	R_{25}	Challenges of relationship between supplier and buyer (Blos et al., 2009)
	Unpredictability	R_{26}	Unpredictability from demand or supply (Pettit et al., 2010)
Capabilities	Information sharing	R_{31}	Sharing information with SN partners (Braunscheidel and Surresh, 2009; Peck, 2005; Blackhurst et al., 2005)
	Efficient staff	R_{32}	Skilled and competent staff (Pettit et al., 2010; Pettit et al., 2013)
	Contract flexibility	R_{33}	Ordering, payment, and shipping part (Duclos et al., 2005)
	Production flexibility	R_{34}	Diverse volume of orders, flexible production schedule (Braunscheidel and Surresh, 2009; Tomlin, 2006)
	Alternative capacity	R_{35}	Support Options (Pettit et al., 2010; Pettit et al., 2013)
	Safety stock	R_{36}	Includes backup storage for critical items (Pettit et al., 2013)
	Process improvement	R_{37}	Process improvement from lead time reduction (Pettit et al., 2010; Tang, 2006; Sheffi, 2005; Peck, 2005)
Proactive Strategy	Design robust supply structure	R_{41}	Build a resilience network to minimize vulnerabilities such as upgrading IT (Carvalho et al., 2012; Scholten et al., 2014; Levalle and Nof 2015).
	Create support capabilities	R_{42}	Short and long-term contracts to provide flexibility (Ponomarov and Holcomb 2009; Ponomarov 2012).
	Establish appropriate agreements	R_{43}	Agreements drawn up between public and private entities to share skills, assets, risks, etc. (Urciuoli et al., 2014; Tang 2006)
	Partnering with the government	R_{44}	This approach promotes public interest in the private sector SC (Gong et al., 2014; Yang and Xu 2015).
	Portfolio diversification	R_{45}	Providing various products to reduce dependence on specific suppliers and products (Urciuoli et al., 2014)
	Supplier selection	R_{46}	Select criteria such as quality, capabilities, … in order to minimize the consequences of disruptions (Pereira et al., 2014; Rajesh and Ravi 2015)

Dimensions	Components	Index	Description and some resources
	Inventory management	R_{47}	Strategic coordination of existing management at the permitted level to minimize inventory risks (Boone et al. 2013)
Reactive Strategy	Use of information technology	R_{51}	Information technology is improving connectivity and supporting other resilience strategies (Erol et al. 2010; Mensah et al., 2015).
	Contingency planning	R_{52}	Forecasting potential events and identifying measures to counter risks and SC disruptions before they occur (Cardoso, 2015; Pettit, 2010)
	Create support capabilities	R_{53}	Information flow and supply capabilities such as reduced cycle time to rapidly recover from disruption (Ponomarov 2012)
	Partnering with supply partners	R_{54}	Ability to collaborate effectively with entities in the SC to respond to disruption and improvement (Scholten and Schilder, 2015)
	Create redundancy	R_{55}	Strategic and selective use of surplus and inventory capacity such as precautionary stocks, multiple suppliers, … (Wang et al., 2015)
	Demand management	R_{56}	Reduce the impact of disruptions through the impact of customer choice such as dynamic pricing, scheduling arrangements, and … (Tang, 2006).
	Supply agility measurement	R_{57}	Ability to respond quickly to unforeseen changes in demand or supply (Carvalho et al., 2011; Mandal, 2012; Scholten et al., 2014)
Outcomes	Readiness for disruption	R_{61}	Prediction and resistance to disruptions (Pettit et al., 2010; Sheffi, 2005; Peck, 2005)
	Response to the disrupt	R_{62}	Accountability and response to disruptions (Pettit et al., 2013)
	Recovery after disruption	R_{63}	Understanding the changes ahead (Pettit et al., 2010; Tang, 2006; Sheffi, 2005)
	Learning after the disruption	R_{64}	Reaction to excellence and accelerated response to disruptions (Pettit et al., 2010; Pettit et al., 2013)

To measure the resilience based on the complex adaptive systems (CAS) approach, the statistical population of this study consists of 11 subsidiaries of the National Iranian Oil Company, including five offshoots of National Iranian South Oil Company (NISOC), namely Karoon, Maroon, Aghajari, Gachsaran, and Masjed Soleiman Oil and Gas Production Company; Pars Oil and Gas Company; Khazar Exploration and Production Company; Arvandan Oil and Gas Company; and the three offshoots of Iranian Central Oil Fields Company (ICOFC), namely South Zagros Oil and Gas Production Company based in Shiraz, East Oil and Gas Production Company based in Mashhad, and West Oil and Gas Production Company based in Kermanshah. Considering the companies with the same task structure, three offshoots of ICOFC were examined. ICOFC, established in Tehran, manages oil and gas production from 80 fields (51 gas, 28 oil, and one gas–oil fields). Of these 80 fields, 13 oil fields and 13 gas fields are in the phase of production. ICOFC supplies roughly one-third of the gas production and covers the central plateau of the country due to the geographical distribution. The main customer of ICOFC is the gas refineries. The gas and condensate are extracted from the fields of ICOFC offshoots and transferred through pipelines to the refineries. The CAS approach employed data obtained from 15 experts working at the so-called offshoots of ICOFC, that is, there is one manager and four experts per company.

3.2. Theory of Complex Adaptive Systems

A review of the theoretical literature indicates that the resource-based view (RBV), the dynamic capabilities approach, and systems theory have been widely used in the history of management theorizing to explain resilience. However, a comprehensive theory has not been developed either in the area of network resilience or in the SC since the basic assumption of the RBV theory is predictable in "logical" environments where the future value of the resources is determinable (Kraaijenbrink et al., 2010). Tukamuhabwa et al. (2015) proposed complex adaptive systems theory as an appropriate tool to study the SCR. They stated that there are inherent similarities between the concept of resilience and the complex adaptive system theory. In other words, CAS mirrors many characteristics of an SCR, including adaptation and coevolution, nonlinearity, self-organization, and emergence.

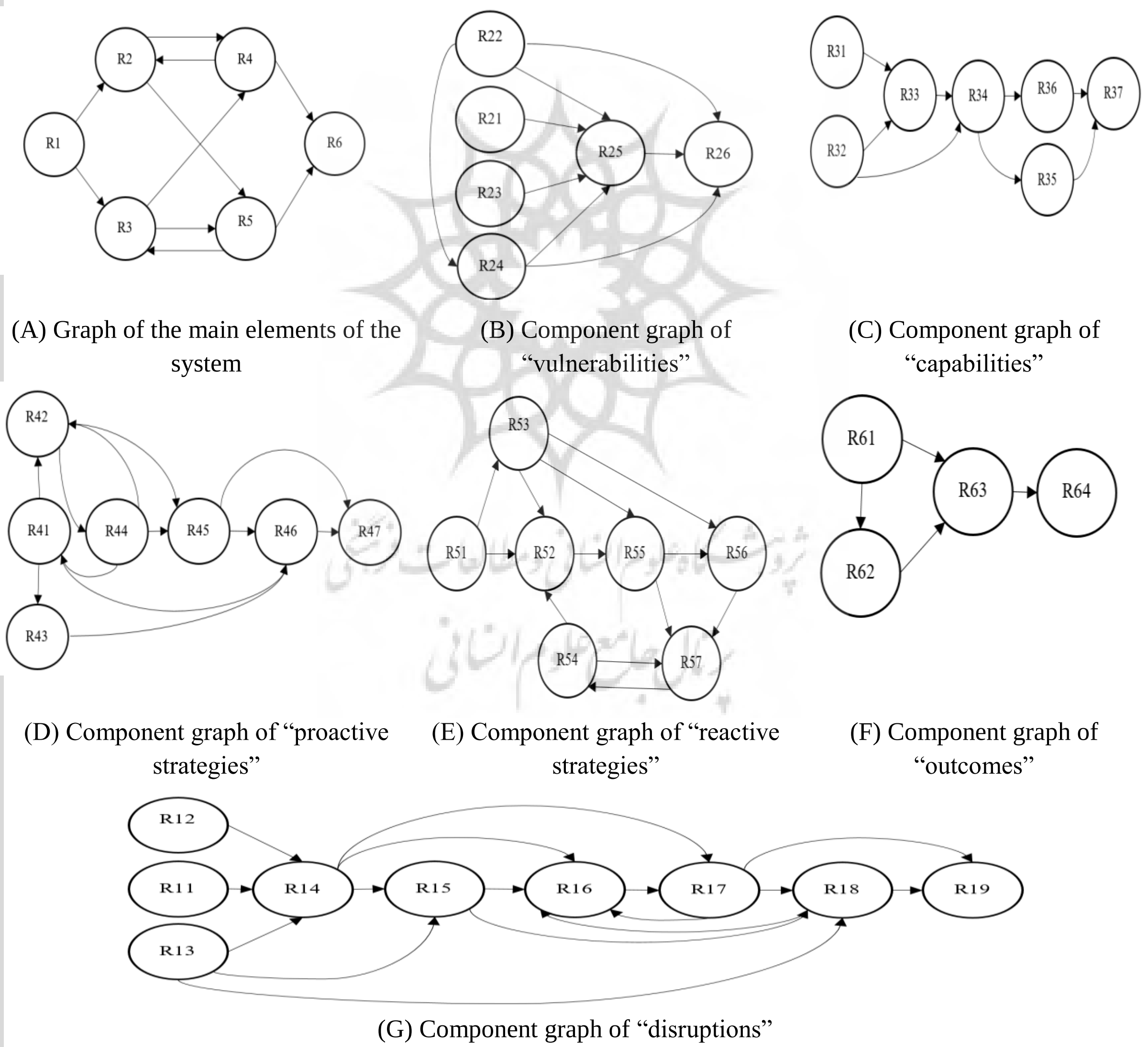
a. Operational definition of SCR with CAS approach

Given the other definitions of the SCR mentioned earlier, as well as considering the identical properties of complex systems theory consistent with the concept of the SCR, this concept can be defined as the adaptability of the entire chain or network for being ready to deal with a malicious event, to respond to it, to recover from it, to learn from it, and to take necessary measures and develop competitive advantage after it (Tukamuhabwa et al., 2015).

b. Graph theory matrix approach in oil and gas companies

Graph theory matrix approach (GTMA) has been employed for modeling and solving a decision-making problem. The steps to implement this approach are as follows (Wagner and Neshat, 2010):

1. **Displaying relationships between factors through directed graph**. Directed graphs are graphical representations of factors and relationships between them, and as the number of factors and relationships between them grows, it becomes more complex and difficult for visual data analysis. To solve this problem, directed graph matrix representation is used (see Figure 9).



(A) Graph of the main elements of the system
(B) Component graph of "vulnerabilities"
(C) Component graph of "capabilities"
(D) Component graph of "proactive strategies"
(E) Component graph of "reactive strategies"
(F) Component graph of "outcomes"
(G) Component graph of "disruptions"

Figure 9. Digraph for selected six dimensions and components.

2. **Matrix representation of a digraph.** While specifying quantitative relationships between factors by experts, a square matrix corresponding to graph ***E*** is obtained in which the entries above and below the main diagonal show the intensity of the relations between the factors and the main diagonal is zero. To consider the amount and size of factors, the diagonal matrix ***V*** is defined where the size of each factor corresponds to the node on the main diagonal. The top and bottom elements of the main diagonal are zero.

$$E = \begin{bmatrix} 0 & a_{12} & \dots & a_{1m} \\ a_{21} & 0 & \dots & a_{2m} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & 0 \end{bmatrix}$$

$$V = \begin{bmatrix} 0_{11} & 0 & \dots & 0 \\ 0 & 0_{22} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0_{mm} \end{bmatrix}$$

By combining two matrices ***E*** and ***V***, the resilience variable permanent matrix (RVPM) which demonstrates the complete relations between factors and the size of each factor is formed as follows:

$$\boldsymbol{RVPM = E + V}$$

The variable permanent matrix of the SNR for W, E, and SZ companies is as follows:

$$\boldsymbol{RVPM_W} = \begin{bmatrix} 1.3\times10^{-7} & .8 & .5 & 0 & 0 & 0 \\ 0 & 1.387\times10^{-5} & 0 & .7 & .5 & 0 \\ 0 & 0 & 3.1\times10^{-7} & .6 & .8 & 0 \\ 0 & .35 & 0 & 2.1\times10^{-6} & 0 & .8 \\ 0 & 0 & .35 & 0 & 8.5\times10^{-5} & .7 \\ 0 & 0 & 0 & 0 & 0 & 2.232\times10^{-3} \end{bmatrix} \quad (1)$$

$$\mathbf{RVPM_E} = \begin{bmatrix} 2.1\times10^{-7} & .8 & .5 & 0 & 0 & 0 \\ 0 & 1.387\times10^{-5} & 0 & .7 & .5 & 0 \\ 0 & 0 & 3.1\times10^{-7} & .6 & .8 & 0 \\ 0 & .35 & 0 & 3.5\times10^{-6} & 0 & .8 \\ 0 & 0 & .35 & 0 & 2.2\times10^{-4} & .7 \\ 0 & 0 & 0 & 0 & 0 & 2.232\times10^{-3} \end{bmatrix} \quad (2)$$

$$\boldsymbol{RVPM_{SZ}} = \begin{bmatrix} 3.3\times10^{-7} & .8 & .5 & 0 & 0 & 0 \\ 0 & 1.387\times10^{-5} & 0 & .7 & .5 & 0 \\ 0 & 0 & 3.1\times10^{-7} & .6 & .8 & 0 \\ 0 & .35 & 0 & 7.7\times10^{-6} & 0 & .8 \\ 0 & 0 & .35 & 0 & 1.3\times10^{-3} & .7 \\ 0 & 0 & 0 & 0 & 0 & 2.232\times10^{-3} \end{bmatrix} \quad (3)$$

3. **The function of RVPM matrix**. This matrix shows the quantitative value and connection between the factors and is known as a determinantal polynomial. However, due to the determinant and negative value in its calculation, some data are missing. Therefore, it has been suggested that the permanent value function should be used instead of the determinant. Thus, neither negative values nor missing data are included in the calculations. The following equation displays the variable permanent matrix of SNR.

The function of permanent matrix consists of *M* + 1 groups which show the quantification of each factor and the relationships between them. The first group represents the value of *M* factor, and the second group does not exist because there is no crown in our directed graph; in other words, each factor does not affect itself. The third group shows the connection between two factors with *M* – 2. The fourth group shows a set of connections between the three factors with *M* – 3. The fifth group consists of two subgroups, while in the first there are two connections and *M* – 4, and in the second four connections and *M* – 4 (Faisal et al., 2007).

In this study, a program has been coded to compute the function of permanent matrix in MATLAB software. Also, to find the optimal and minimum values of the SCR, one can consider the factor sizes, which are the main elements of the RVPM diagonal, as the highest and lowest values, and calculate the function of permanent matrix. Consequently, the optimal and real values of the SNR will be obtained, as listed in Table 6.

$$
\begin{aligned}
Per\ (RVPM) = {} & \prod_{i=1}^{M} A_i + \sum_{i,j,\ldots M} (R_{ij}R_{ji})\, R_k R_i \ldots R_M \\
& + \sum_{i,j,\ldots M} (R_{ij}R_{jk}R_{ki} + R_{ik}R_{kj}R_{ji}) R_i R_m \ldots R_M \\
& + \Bigg(\sum_{i,j,\ldots M} (R_{ij}R_{ji})(R_{kl}R_{lk})\, R_m R_m \ldots R_M \\
& + \sum_{i,j,\ldots M} (R_{ij}R_{jk}R_{kl}R_{li} + R_{il}R_{lk}R_{kj}R_{ji})\, R_m R_m \ldots R_M \Bigg) \\
& + \Bigg(\sum_{i,j,\ldots M} (R_{ij}R_{ji})(R_{kl}R_{lm}R_{mk} + R_{km}R_{ml}R_{lk}) R_n R_o \ldots R_M \\
& + \sum_{i,j,\ldots M} (R_{ij}R_{jk}R_{kl}R_{lm}R_{mi} + R_{im}R_{ml}R_{lk}R_{kj}R_{ji}) R_n R_o \ldots R_M \Bigg) + \cdots
\end{aligned}
\tag{4}
$$

Table 6. Paired comparison of the optimal and current values of the resilience of the SNs.

Optimal value	Resilience of SN "W"	Resilience of SN "E"
9.406×10^{-11}	3.057×10^{-11}	4.938×10^{-11}
100%	32.5%	52.5%
Optimal value	**Resilience of SN "W"**	**Resilience of SN "SZ"**
1.787×10^{-10}	3.057×10^{-11}	7.76×10^{-11}
100%	17.11%	43.42%
Optimal value	**Resilience of SN "E"**	**Resilience of SN "SZ"**
1.787×10^{-10}	4.938×10^{-11}	7.76×10^{-11}
100%	27.63%	43.42%

c. Comparison between directional graphs

Studying the SNs shows that they are comparable in terms of the amount and degree of resilience provided that the graphs of the SNR and the permanent matrix of the SN are similar. Then, the coefficients of dissimilarity and similarity are issued (Soni et al., 2014). In Table 7, the parameters V and V' are the numerical values of the permanent matrices of the two compared SNs. The dissimilarity and similarity coefficients are calculated through the equation for C_d and C_s respectively.

Table 7. Coefficient of dissimilarity and similarity.

Equation	Description
$C_d = \lambda / U$	Coefficient of dissimilarity
U=MAX [| V | and | V' |]	Maximum constant value of the permanent matrices
$\lambda = \lvert V - V' \rvert$	Absolute difference of the constant value of the permanent matrices
$C_s = 1 - C_d$	Coefficient of similarity

The values of C_s and C_d are between zero and one, and the more the two SNs are comparable in terms of resilience, the closer the coefficient is to one. The similarity coefficient of the studied networks can be seen in Table 8 which shows that the similarity coefficient between E and W is 0.619, between W and SZ is 0.394, and between E and SZ is 0.636. These values indicate that there is a significant difference between the SNs of W and SZ regarding resilience. However, compared with E and SZ as well as E and W, this difference is smaller as if it is closer to similarity.

Table 8. The resilience of SNs through the similarity coefficient.

SN Equation	E and SZ	W and SZ	W and E
$C_d = {}^{\lambda}/_{U}$	0.364	0.606	0.381
U=MAX [$\vert V \vert$ and $\vert \acute{V} \vert$]	7.760×10^{-11}	7.760×10^{-11}	4.938×10^{-11}
$\lambda = \vert V - \acute{V} \vert$	2.822×10^{-11}	4.730×10^{-11}	1.881×10^{-11}
$C_s = 1 - C_d$	0.636	0.394	0.619

4. Conclusions

This paper presents a multidimensional analysis of resilience in the field of SN literature and develops a new typology of SNR based on qualitative and quantitative methods for measuring the SNs in oil and gas production companies. The main findings of this paper are to represent a two-phase approach to measuring and evaluating the resilience of SNs. The conclusions drawn from the results of the current works are as follows:

- Applying the SLR based on the CIMO-logic analysis: This approach fills the existing gap in the literature of the SNR. Most of the researches on resilience in general and economic resilience in particular (Dormady et al., 2018: 40) lack a solid theoretical foundation. Moreover, many quantitative studies have only addressed the measurement of resilience. On the other hand, in many qualitative studies only the frequency of theoretical literature of resilience has been examined. However, the current study attempted to overcome the abovementioned limitations by presenting a comprehensive framework and specific classification of studies related to resilience, including resilience strategies, its future orientation and planning, its measurement and evaluation, and its theoretical and conceptual framework.
- CAS approach: Many quantitative or qualitative studies are not capable of comparing the resilience of the SNs. However, this study has resolved this issue by applying the CAS approach. Given that much of the previous literature on resilience is based on the measurement of an independent chain/network resilience, the quantitative approach used in this article is CAS that not only does it quantitatively assess the resilience of the SN, but it also compares the resilience of networks.
- As the number of companies increases, paired comparison of resilience in companies is highly inconsistent. Therefore, applying other methods and techniques for evaluating and ranking, including multi-criteria decision making methods (MCDM), is suggested. MCDM methods which rank the alternatives in different ways consist of combined compromise solution (CoCoSo) methods, simultaneous evaluation of criteria and alternatives (SECA), best worst method (BWM), and multi-attributive ideal–real comparative analysis (MAIRCA). In the case of varied rankings in the abovementioned methods, average methods, such as Copeland and Borda, can be used for comparison as aggregation methods.

The findings of this study can make major contributions to the future studies. As mentioned before, by classifying the most significant studies on resilience, the present study helps firms and organizations to measure the SNR.

At its most basic level, the analysis can be applied to each firm in the chain. While we acknowledge that, at the most disaggregated level, SCs are composed of firms that can each implement their own resilience actions; we also confirm that the complexity and interdependence of the SCs extend well beyond a single firm.

We acknowledge that SNs consist of different firms each of which takes its own resilience measures. On the other hand, we believe that the complexity and the interdependence of the SNs are beyond a simple firm. Therefore, comparing the resilience of the SNs relying on quantitative approaches based on the CAS theory can significantly help the decision makers and stakeholders in the field of supply management. This is especially true for the contexts in which the organizations face different political or international challenges such as sanctions or embargos. As sanctions or embargos begin to squeeze the economy, the organizations should develop resilience strategies to deal with resistance economy. Given the above facts, employing comprehensive approaches based on the SLR and the quantitative methods such as the CAS in such contexts is of great importance.

As discussed earlier, the literature on the SN obviously emphasizes the application of theories such as RBV and resource allocation models (Hosseini et al., 2019; Dormady et al., 2018). Moreover, the findings of adopting the two-phase approach in this study are also in line with the findings of Hosseini et al. (2019). The results showed that SNR metrics, addressed at the level of organizations in this study, can be expanded in future studies to contain the entire SN.

It may happen for many firms to be hard struck with disasters if they are not able to predict post-disaster damage and become fully prepared to deal with them. However, the results of the current study highlight that taking resilience measures before planning can reduce losses and build up resilience capacity.

Moreover, an important issue emerging from these findings is that organizations need to develop adaptive approaches so as to compare the results of resilience with SN stakeholders, partners, and competitors. The ever-increasing growth of the two-phase approach indicates the application of updated resilience approaches and techniques in measuring, evaluating, and comparing the resilience of the SCs and SNs.

This study can serve as a foundation for future studies. In other words, future studies will go beyond examining the resilience of the SNs of oil and gas companies. Furthermore, the results of the present study suggest implementing new approaches for measuring and evaluating the resilience of multi-product SNs.

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