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A REVIEW ON ENERGY SUPPLY CHAIN RESILIENCE THROUGH OPTIMIZATION

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Abstract

The concept of supply chain resilience continues to attract both industry and research experts in the field of energy. These stakeholders continue to tackle disruptions to supply chain systems through the introduction of strategy options for resilience. A better understanding of broader dimensions of potential disruptions to supply chains caused by uncertainties has become eminent, especially as currently experienced during the global COVID-19 pandemic. The effects of the outbreak in disrupting supply chains in the energy sector will, in the next decade, continue to be a likely concern for industry and research stakeholders. Balancing the increasing need for energy security to meet the continuous growth in energy demand through shortage reduction and increased uptime using optimization is the core of this research. This review paper provides an insight into recent studies in the field of natural gas supply chain resilience as a major player in the energy mix, and the continued disruption and subsequent shutdowns of plant nodes, which results in emission loss to the environment. This paper is motivated by the disparity between demand and supply triggered by the disruption of supply chain networks. This paper referenced scientific work on supply chain resilience of biomass, water, power systems, and natural gas. Findings show that existing studies favor fewer system-based strategies in optimizing for resilience. This review concludes that optimization is a useful tool to continuously achieve resilience in supply chain production, storage, and transportation activities.

Keywords: Resilience, Supply chain, Optimization, Energy, Natural Gas, Uncertainty, Disruption, COVID-19.

Abbreviations:

Bcm	- Billion cubic meters	Mcf	- One thousand cubic feet
CO2	- Carbon dioxide	Tcf	- Trillion cubic feet

Word Count: 7,771

Highlights

- Review of the resilient supply chain
- Presentation of various disruptions impacting the supply chain
- Highlighting losses and shortages recorded during shutdowns
- Presentation of natural gas and other energy supply chains
- Emphasizing the development of the resilient supply chain system for natural gas through optimization in the wake of rising global demand for energy

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1. Introduction

1.1. Disruptions to supply chain

A supply chain is an integrated network of facilities that varies significantly in complexity and scale [1–3]. Although there are some simplified structured supply chains, the energy system supply chains are usually more complicated, as shown in figs. 1 to 3, thereby affecting their smooth operation even without interference. Several challenges impact the continuous functioning of supply chain networks. These challenges increase the complexity and vulnerability of specific supply chains, making them susceptible to disruptions [4]. Such interruptions include breakdown of infrastructure, routine or emergency shutdowns (planned and unplanned), conflicts, attacks, environmental disasters, theft, unexpected delays, queuing, demand variation, a shortfall in inventory, inefficient supply capacity, and political upheavals [5]. Supply chains have a long history of disruptions caused by both exogenous and endogenous factors. The exogenous disruption is beyond the control of the plant operators and field engineers. External factors like climate change, political instability, pandemic, war, illicit or violent strike, sea piracy, sabotage, vandalism, and riots are primary causes. The peculiarity of uncertainties associated with weather conditions and energy demand makes it more difficult for near accurate modeling. In contrast, endogenous disruptions are within the control of the operators. Internal factors like plant engineer error and technology failure [6] are common causes.

Disruptions in a supply chain are usually low in occurrence, yet the economic and social impacts are significant [6–8], meaning that disruption results in associated costs. Preventing or reducing the disruption period will help reduce the cost burden and increase supply. Unlike disruption, coping with uncertainty is one of the most significant problems in the supply chain system. It poses challenges in the analysis of performance [9] even though the impact may be minimal. For instance, the uncertainty around the current pandemic caused by the COVID-19 outbreak, which saw demand for oil drop drastically, is a rare occurrence making it impracticable to use it to analyze the current energy supply chain's performance. However, this type of uncertainty comes with a high impact on the supply chain of essential commodities such as food, medical supplies, and clothing, generally due to disruptions to the regional transportation network. The ripple effect of the COVID-19 pandemic across all supply chains will last for a long time to come. Such a novel type of uncertainty requires several realistic factors for proper optimization modeling. Disruption and uncertainty sometimes are used interchangeably, and they present a significant challenge to the supply chain. The purpose of addressing these occurrences and their potential impact through supply chain optimization is to increase system resilience. The motive of this paper is to present a comprehensive study of supply chain resilience, which focuses on system flexibility, reduction in emission losses, and delivery uptime as it relates to the natural gas supply chain in the event of disruptions leading to emergency shutdowns. The study integrates ideas from natural gas and other energy sources on supply chain resilience.

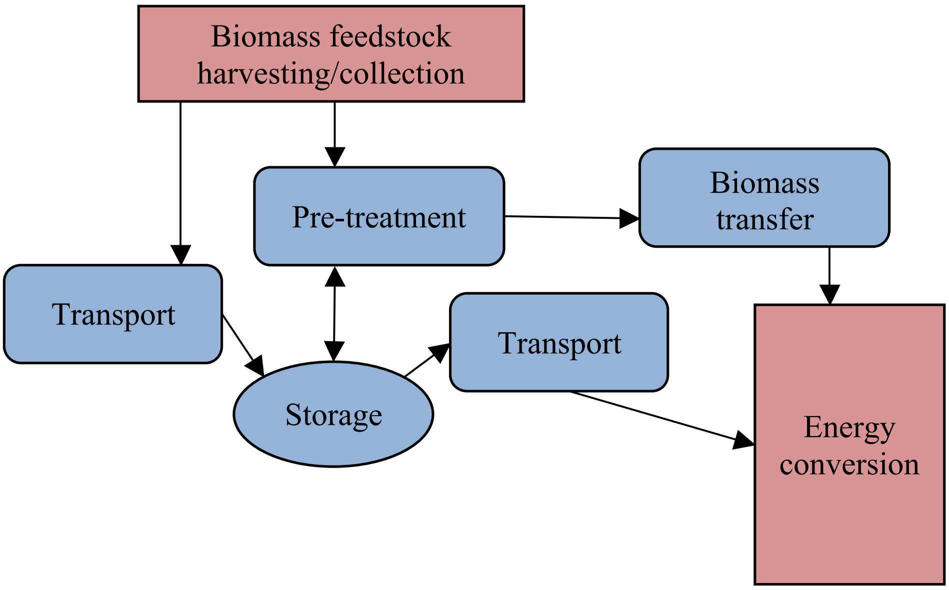

Figure 1. Biomass supply chain. Adapted from [10]

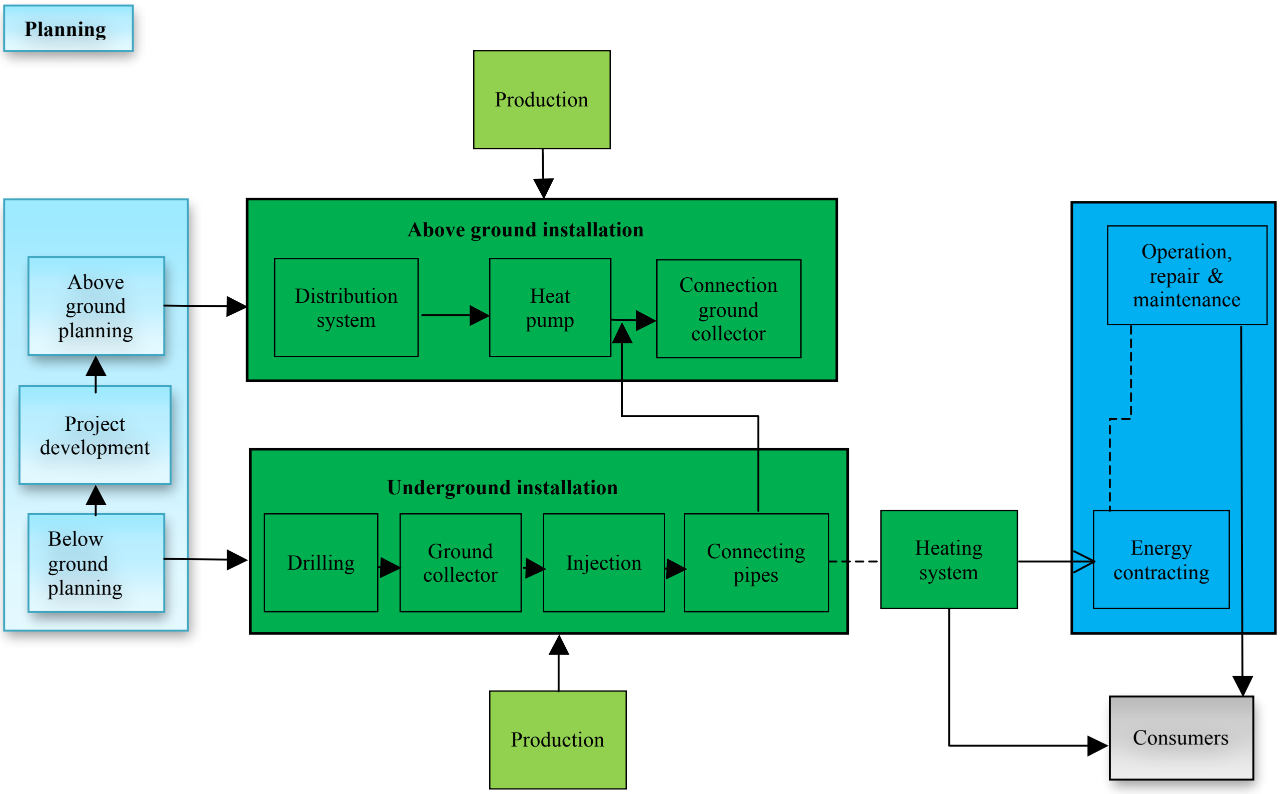

Figure 2. Geothermal energy supply chain. Adapted from [11]

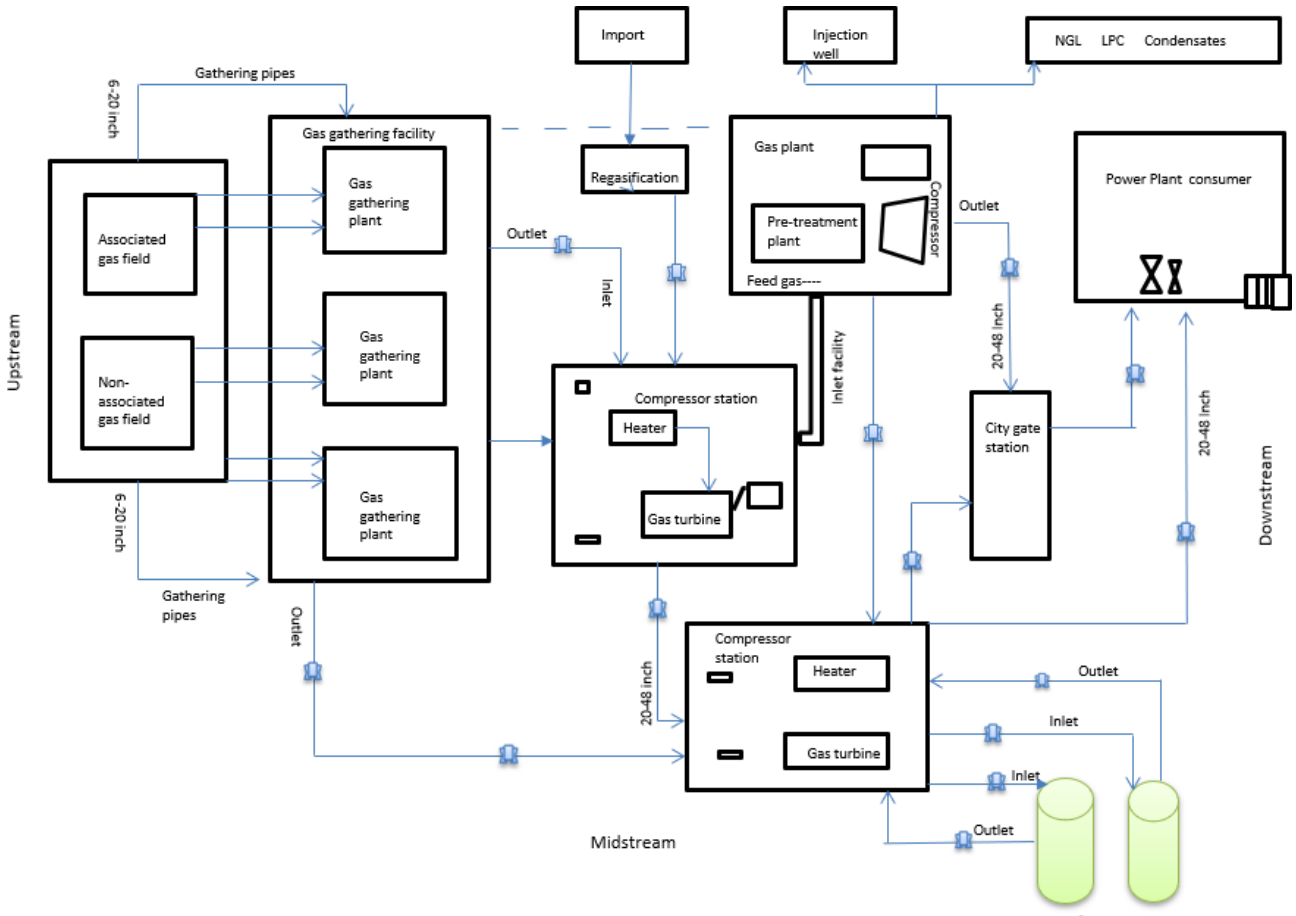

Figure 3:Complex natural gas supply chain

1.2. *Categorization of supply chain*

Supply chain categorization is according to the need to measure the system's performance, which may be possible to derive a diagnostics control mechanism. The classification is infrastructure design, policy formulation, and planning and scheduling [12]. While the first two categories are pre-operating activities, the last one deals with the actual operation flow in the supply network. Infrastructure design and policy formulation are offline activities that establish the best option to design and manage supply chain networks, whereas, planning and scheduling category attempts to operate the existing network for optimal response to conditions that affect the supply chain [12]. For the infrastructure or network design, trade-offs such as cost disparity based on location, production intricacy and efficiency, identifiable network pathways, and exchange rate variances result in realistic analysis using the appropriate model. These trade-offs will determine the location of network infrastructures such as processing plant, transportation, and storage, sourcing and allocation decisions, and expansion or significant alterations to existing infrastructure. The simulation and policy analysis entails establishing the optimal procedure for the design and management of supply chain networks [10]. Decisions are continuously adjusted in the planning and scheduling problem type, to optimize the network with given established constraints. These three problem categories occur in tandem with the three decision level hierarchies based on time horizons [5,13]. The three decision levels are strategic, tactical, and operational activities. A summary of the hierarchy of these decision levels is shown in Table 1.

Table 1 Summary of decision level hierarchies

Decision level	Time	Problem category	Activity	Data requirement	References
Strategic	Long term	Network design	Design of network distribution, location the of the facility (production, storage, and distribution)	Estimated & accumulated data	[14–19]
Tactical	Medium Term	Simulation & policy	Distribution planning, production planning, inventory management, & contract evaluation	Non-transactional data	[5,20–23]
Operational	Real term, daily, or short	Formulation, planning and scheduling	Replenishment & delivery operation	Transactional & accurate data	[15]

Infrastructure capacity, management of material input flow, availability and reliability, demand fluctuation, contracting of supply at the beginning, and transportation planning, are key factors to consider in estimating the success of a supply chain network. Accordingly, cost and customer responsiveness are used predominately as measures of supply chain performance [24]. Cost minimization and profit maximization are the related cost indicators of performance measurement. Cost minimization includes inventory and operating costs while customer responsiveness measures lead time, stock out probability, and fill rate. Profit maximization is measured in the form of benefits and revenues, increased system flexibility in volume and flow rate, service level maximization, return on investment, just-in-time, and backorder minimization.

This paper presentation is as follows. In section 2, an in-depth analysis of supply chain resilience is introduced, which covers the various strategies that different supply chain systems have adopted to attain resilience. Also presented in this section is the summary of the literature on supply chain resilience. In section 3, the supply chain of energy and natural gas is presented, grouped into upstream, midstream, and downstream activities. Presented in section 4 is the resilience of the natural gas supply chain. Section 5 summarizes the different optimization techniques used in modeling supply chains. Finally, section 6 presents the concluding remarks and discussion.

2. The resilience of supply chains

2.1. Defining supply chain resilience

The idea of resilience has gathered considerable momentum in recent years [25,26] such that various researchers have studied it as a broad topic and how it affects supply chain systems [27–29]. Resilience is a concept that denotes both strength and flexibility used in practically all disciplines of research [30]. The continuous functionality of a supply chain network depends on its ability to react to interference swiftly and to return to its original or a desirable state before the disruption [4,24,29]. The swift reaction could also be known as the adaptive capacity of the system [31] that makes it sustainable and, in response to disturbance, echoes the system's learning behavior [32]. Although there is generally no accepted definition of resilience, [25,33,34] defines it as the capacity of a supply chain network to overcome stress or system failure and mitigate the impact of disruptions as much as possible. A broader accepted definition is the system's ability to return to its original state or move to a more desirable state after its disruption [25]. Regarding energy systems resilience, the UK Energy Research Center [35] defines it as an intrinsic characteristic of the system to build capacity that tolerates disturbance to energy flow through speedy recovery or provision of alternative means of satisfying energy needs. The scope of resilience as an area of research can cover technical, economic, environmental, social, and policy aspects. Therefore, the measurement of the system's performance in terms of economic losses or gains, casualties, external impact, and recovery time covers the resilience scope.

Although these various definitions cover the idea of resilience, [31] argued that resilience should move from its metaphoric description to actual measurement. In line with this argument, researchers have carried out measurable system-based resilience over the years. For instance, [36] measured an infrastructure based resilient supply chain by providing inventory and backup systems while [37] introduced topology redundancy for a water distribution network targeted at increasing hydraulic reliability and the continuous supply of water during pipe failures. Whereas for the operational based resilient supply chain, the use of multiple sourcing of suppliers to combat disruption and downtime in the supply chain was introduced in [38] while in [39] the gas contracts, fuel consumption and on/off-grid operation of the plant generators were modeled for power system resilience.

Moving towards broader-based management of supply chains susceptible to disruption is critical in modern-day adoption of resilience as proposed by [25]. In addition to strategies adopted to improve or sustain supply chains, collaboration is required between different players in information gathering and sharing to mitigate potential risks and impacts. The collaboration is essential where there are possible uncertainties as it delivers a better profile from the suppliers to the consumers of the supply chain by providing a broader view of an extended supply chain. Without great interfaces with other critical components, a significant improvement to the supply chain may be unattainable by directly modifying only transportation and business processes [12].

2.2. Strategies for achieving resilience

In recent times, different researchers have adopted various strategies to achieve supply chain resilience irrespective of the product type. Mitigation strategy, recovery strategy, and passive acceptance are three disruption management approaches that can be adopted for any supply chain type [40]. Mitigation entails the preparedness before disruption such that actions are taken in advance to plan for disruption occurrence. Recovery implies the dexterity in restoring the supply chain after the disruption. Whereas passive strategy expects nothing to be done such that the disruption and disturbance periods are the same [26]. Presented in the next subsection is a detailed explanation of these three strategies.

2.3. Assessment of resilience

Mitigation planners estimate vulnerability to disruption and take anticipatory actions to lessen risk and exposure. Over the years, some of the adopted mitigation strategies include additional production and supply capacities for expansion, the introduction of alternative transportation routes, multiple sourcing, inventory expansion, the introduction of backup facilities, and simplifying the supply chain network. For instance, to forestall the consequences of system failure in municipal water distribution, [37] asserts that the system designers used the concept of topological redundancy by introducing pipes and closing loops to enable flow to reach given nodes from alternative routes in the event of system failure. Analyzing the uncertainties confronting the biomass supply chain, [13,41] argues that there is a need to develop inventory and fleet management models, while [42] suggests introducing a regional pre-processing plant may be necessary to provide resilient biomass supply chain. The increasing use of microgrids enhances resilience during major disruptions [43] for power systems as they can be isolated from the primary grid or integrated to support a network that is experiencing insufficient supply. Similarly, [39] looked at the operation flexibility of power plant systems and natural gas systems by modeling their physical and economic interactions to ensure the resilience of power generation systems. For natural gas resilience, [33] proposed using a decentralized controller to regulate congestion during a disruption in a pipeline network to distribute the available capacity to each node to maintain network throughput.

Although adverse weather conditions vary from location to location, an earlier work proposed deliverability of storage in gas planning as mitigation for natural gas supply shortfall [44]. In contrast, [45] proposed a retrofit strategy to include emergency shutoff valves along the pipelines to prevent gas leakage caused by earthquake disruption. In addition to mitigation efforts, [46] suggests that lessons from climate extremes adaptation, such as modifications to practices and procedures can be adopted to minimize environmental disruption. This consideration has been introduced for transmission and distribution system resilience to mitigate the impact of extreme weather conditions using alternative solutions for real-time information, provision of microgrids, and comprehensive weather forecast considered critical during the disruption [27,47].

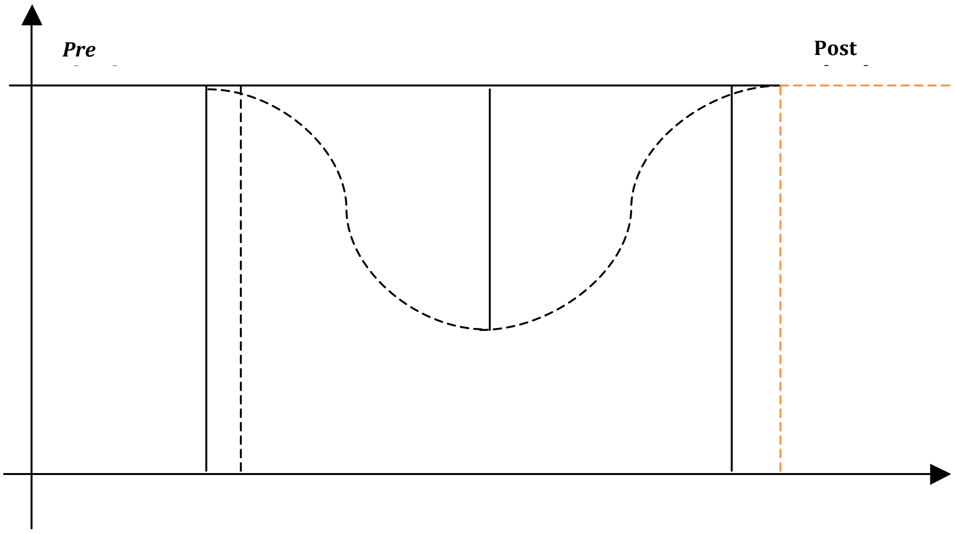

Figure 4. Disruption period (t) and loss from a plant shutdown

Displayed in fig.4 is the impact on the functionality of the supply chain network during the disruption. Interruptions usually result in shutdowns, during which there are slack periods that are allowable. Excess inventory from storage mitigates the shortfall. However, if the shutdown period exceeds the allowable duration known as prolonged shutdown, then a loss is inevitable, becoming a burden. The goal of a mitigation strategy is to avoid such occurrences.

Recovery strategy involves the steps taken after a disruption occurs. An example is seen in [28], where the research aim was to devise the most efficient way of tackling and restoring an interdependent infrastructure system to normalcy after partial destruction occurs using an optimization technique. The resilience triangle recovery as a strategy tool for analytical assessment was presented in [30], while [27] used it to describe the loss during a disruption. The measurement of resilience is a function of the functionality of the plant. The impact of the loss is measured by:

(i)

Where: I = impact of the disruption, St = start time of the disruption, Ft = end time when recovery is completed, and k = the plant functionality at the time (t). Presented in fig. 5, is the plant functionality (k) and the time (t) in the vertical and horizontal axes. The normal state (NS) before the interruption at R(S_t) shows a 100% performance rate according to the plant's specified functionality. After the interruption occurs, the recovery process takes place. The recovery time is critical, and the expectation is that the plant functionality goes back to 100% using the concept of resilience. The recovery is fully achieved at R(F_t) when the recovery implementation state is at Ft.

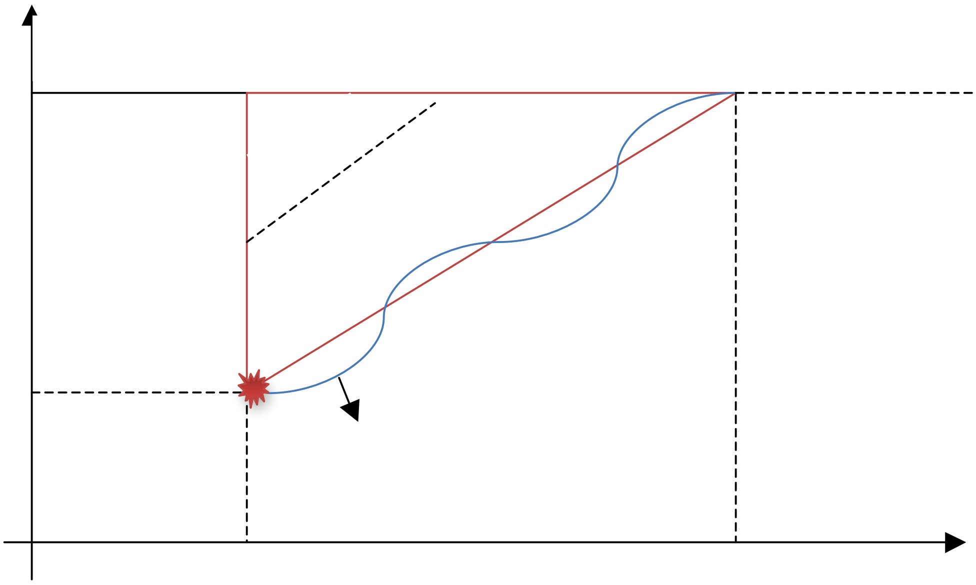

Figure 5. Resilience triangle associated with plant disruption. Adapted from [30]

In fig. 5, passive acceptance occurs when the plant's functionality drops to 35%, with no recovery action taken. No action is required because the costs may outweigh the benefits. All three strategy types are dependent on the cost and what is of priority to the firm. The complexity of a supply chain impacts its resilience according to [34]; therefore, complex supply chains like nuclear power are less resilient than smaller-scale technologies such as solar photovoltaic (PV). Therefore, a complex supply chain can have significant barriers like infrastructure innovation with several bottlenecks that are not easy to resolve. Currently, the introduction of micro-generation and decentralized grids has promoted sophisticated resilience in the energy sector.

Based on open literature, the developed resilient supply chains are either system based [4,33,39] or operation based [30,42]**.** For instance, in dealing with a system based resilient supply chain, inventory and backup systems were analyzed in [36], while [37] introduced topology redundancy. Whereas for an operation based resilient supply chain, the use of multiple sourcing of suppliers to combat disruption and downtime in the supply chain was introduced in [38] while the gas contracts, fuel consumption and on/off-grid operation of the plant generators where modeled in [39]for power system resilience. Table 2 classifies literature studies across different supply chains.

Table 2: Classification of literature in supply chain resilience studies

Article referenced	Resilience index	Supply chain activities modeled	Constraints	Objective functions	Product type Network	Cause of disruption
[43]	*Microgrids*	*Distribution*	Time prediction, renewable intermittency	Outage management, proactive scheduling	Power systems	Natural disaster
[39]	*Interaction between power systems & gas systems*	*Transmission*	Capacity & virtual attacker's budget	Operation performance max & cost min	Power systems & natural gas	Natural disaster & man-made
[28]	*interdependency*	*Regional distribution*	Time & resources	Cost min	Critical infrastructure networks	Natural disaster, human & equipment failure
[27]	*Enhancement of physical hardiness*	*Distribution*	Operation capability & restoration time	Functionality loss min & restoration time min	Power grid	Equipment failure & natural disaster
[42]	*Regional pre-processing plant*	*Processing*	Location	Cost min	Biomass supply chain	Equipment failure & natural disaster
[33]	*Decentralized controller*	*Transmission (communications)*	Congestion	Supply max and loss min	Natural gas	Conflicts & crises
[48]	*Storage facility, inventory routing, and fleet scheduling system*	*Inventory & transportation*	-	Cost min	LNG supply	General

[4]	*Flexibility & redundancy*	*Transportation*	Material flow	Lead time & cost min	Automotive supply chain	Strike & natural disaster
[36]	*Inventory & backup facility*	*Distribution*	Location	Cost min & service level min	Consumer packaged goods	General
[38]	*Multiple Sourcing*	*Supply*	Capacity	Cost min through diversification max	General supply	Supply inadequacies
[7]	*Open/shut flexibility of plant & shipment quantities*	*Distribution*	Capacity	Profit max & risk min	Global supply	Supply & demand shortfall, human & natural disaster
[5]	*Management planning*	*Production & distribution*	Operation time	Cost min	General multi-shop supply chain	System breakdown & delays
[37]	*Topology redundancy*	*Distribution*	Availability	Cost min & resilience	Water supply chain	General

3. Energy supply chain

The energy supply chain typically involves a network of supply, production, transport, storage, and consumer [49] interconnected by physical and financial infrastructure, information sharing, and conveyance. The provision of functional and responsive supply chains through optimization to meet rising energy demand has become imperative. Guaranteed energy security is when the supply chain resilience can deal with stress and shock to ensure continuity of supply [34]. Research shows that the availability and affordability of energy are considered essential for sustained economic growth [50–52]. Consumer demand is becoming increasingly sophisticated, and a significant success metric is to meet medium to long-term supply in a sustainable manner [53]. A rising concern is whether the current systems will be able to cope with future global energy demands projected to increase over a 23-year (2017-2040) period by 25% [54]. Table 3 shows that the projected global consumption of energy rose to 2.9% in 2018, from 2.2% in 2017 [55].

Table 3: Contribution of primary energy consumption growth. Source [55]

Energy source	**2018**	**2017**	**2016**	**2015**	**2014**
	%	%	%	%	%
Oil	1.5	1.8	1.6	1.9	0.8
Natural gas	5.3	3	1.5	1.7	0.4
Coal	1.4	1	-1.7	1.8	0.4
Renewable, hydro & nuclear	14.5	17	14.1	4.1	6.8
Global primary consumption growth	2.9	2.2	1	1.0	0.9

Solution techniques are developed for energy supply chains to improve the supply network. There are essential efforts in place that allow for technology development, policy and market changes, and economic investment options directed towards the expansion of energy optimization planning models to mimic market behavior [56]. For instance, the introduction of a cheaper storage facility by [56] allowed for cost optimization in a biomass supply chain and the use of multiple design planning for a bio-fuel supply chain design where uncertainties are minimal [57]. Open economies and stakeholder involvement in all business aspects, widened by the motivation of commercial competition, have aided the introduction of new technologies in energy generation and delivery. Newer technologies produce fewer pollutants and are highly efficient [58]. These technologies apply to conventional (coal, oil, gas, hydro, nuclear) and unconventional (solar, wind, fuel cells) sources of energy. For lack of time and space, in this work, we will focus majorly on the natural gas supply chain as a significant strategic player in the energy mix.

3.1. Natural gas as an energy source and its environmental impact

Natural gas is one energy source for which there has been a consistent growth in demand from 2016 to the present. Research in 2018 showed the potential of natural gas as it accounts for a 45% rise in global energy consumption [59]. Natural gas use rose globally by 5.3% or 195 billion cubic meters (bcm) equivalent [55] against 96 bcm in 2017 [60]. Attributed to the demand growth is the capacity to be supplied to a wide range of sectors, ample availability that is estimated to be 194791.59 bcm or 6,879 trillion cubic feet (tcf) globally, its relatively low greenhouse gas impact compared to other fossil fuels [61], and reduced capital cost [62]. However, some researchers have argued that different gas emission types, such as vented, fugitive, and combustion, provide methane emission during start-up, normal operations, maintenance, upset, and mishap activities causing major damage to the environment [63]. For instance, on a weight basis, methane, a major component of natural gas, is 23 to 25 times more radiatively potent than CO2 based on a 100-year interval Global Warming Potential (GWP) and poses a challenge if emitted [64,65]. In contrast, a 1996 study converted methane to CO2 equivalent emission using the GWP scale values of 34 and 6.5 with corresponding time ranges of 50 to 500 years, respectively, and concluded that methane had a lower impact than CO2 based on global warming [63].

Notwithstanding, natural gas is an essential fuel for heating, electricity generation, and industrial processing. As energy demand continues to rise, natural gas fuel supply to combined cycle units is increasing. It is a cleaner conventional fuel and more efficient means of energy generation in a competitive market. It is also the cleanest and most hydrogen-rich fuel source, coupled with its high energy conversion efficiencies for power generation. [62]. It has consistently been a reliable source of energy and currently a bridge fuel between conventional and renewable energy sources in most countries. Although the drive for renewable energy sources to replace fossil fuels is increasing due to the associated significant CO2 emissions, natural gas is an intermediary between renewable and conventional fuels. As such, the development of gas to power technologies reduces CO2 emissions, resulting in relatively better environmental performance.

3.2. Natural gas supply chain

The natural gas supply chain, as shown in fig.3, is composed of critical, vast, and complex infrastructure. The production process design and management are within the production planning of the supply chain, while the transportation element is the combination of both the transmission and distribution. In the transportation echelon, the flow of the product to the compressor unit and the city gate station falls within the transmission level while the flow from the gas company and city gate station to the consumers are within the distribution level of the gas supply chain.

3.2.1. Description of the gas supply chain network

As in any supply chain system, the natural gas network consists of several nodes that are interconnected. These nodes can be analyzed to increase supply, reduce losses, and lower costs. The analysis includes detailed modeling of the pipeline, processing plant, compressor, storage facility, and city gate station. The complexity of the system poses challenges for those managing the network because different operators and partners usually run individual components. For instance, pipelines can be managed and owned by private companies or by the host government, depending on the country and the policies applicable. In the UK, a significant pipeline network transporting about 30% of the nation's oil from the North Sea is owned and operated by a private firm. In other countries, the entire transportation network is owned and operated by the federal government's subsidiary firm, while in the US, a large portion of the pipeline infrastructure operated by private companies with millions of investors as owners. The upstream, midstream, and downstream are three primary activities in the natural gas supply chain network, and each of these elements is linked. The upstream is the extraction of both associated and non-associated gas from oil and gas fields, respectively. Here, all extraction and exploration activities are deployed. The transmission of the refined gas from the processing plants to the city gate station is in the midstream. In the downstream are storage and distribution of the processed product to consumers in the form of heat, power, and air-cooling.

3.2.2. Gas field

Natural gas is extracted from a reservoir at elevated pressure and temperature (P, T) and consists of a mixture of hydrocarbon and non-hydrocarbon gaseous substances. Typical natural gas composition is primarily methane with lower percentages of ethane, propane, and butane, often accompanied by fewer impurities such as carbon dioxide and nitrogen. Natural gas producing countries have different supply streams, harnessing these sources for reliable material availability is crucial. If there are different sources available for material input, the aggregate supply should meet the total demand.

3.2.3. Compressor

Compressors are among the most complex and vital components of a gas network system [65]. Several compression units are in a single compressor station, and they are mainly used to reduce the volume and raise the pressure of natural gas to increase flow along the pipelines. Compressors are used to overcome the pressure drop that occurs in a long-distance gas transmission pipeline. Some of the most frequently used compressors are centrifugal and reciprocating, which are characterized by a centrifugal dynamic movement or through reciprocating positive displacements, respectively. The machine can be used as a baseload or a peak load compressor. The baseload compressor operates in a yearly cycle most of the time and has only 500 hours of downtime on an average. The peak load compressor operates only about 4000 hours a year but turned on and off up to 40 times in an annual cycle. Compressors receive gas at pressures ranging from 200 to 600 psi and compress it to about 1,000 to 1,400 psi before entry into the main pipeline [62]. Additional processing can be done by the compressor scrubbers and filters that extract any liquids and remove particulate matter that may be found in the gas stream. Compressors can be coupled in stages in a compressor station, depending on the needs of the pipeline. They are usually located every 40 to 100 miles along the gas transmission route. Supply and demand can directly affect the level of compression required for the flow. Other components along the transmission pipeline needed to control and facilitate gas flow are valves and regulators. The valves, regulators, and compressors are known as active or controllable network elements, while the pipeline is known as passive.

3.2.4. Storage

Along with gas reservoirs or gas holders, the pipeline is used for temporary short-term gas storage, known as line packing. There are three widely known underground storage types: depleted gas reservoir, aquifer reservoir, and salt caverns. The storage system can be set up at different points along the supply chain, between the transmission and distribution system. The benefits of underground storage range from safety, significantly higher and cheaper storage volumes, ideal for peak demand periods, and environments where pipelines are susceptible to vandalism. Where storage relies on online packing, there is a limit to which the pipeline can store gas.

3.2.5. Processing plant/refinery

A refining plant processes the gas to meet the available pipeline transportation standards and specifications. This means that the gas is almost entirely methane when it is dry, and all other associated hydrocarbons removed [65]. The composition of natural gas can be reported in terms of mole fraction (mole percentage), mass fraction (weight percentage), or volume fraction (volume percentage). Non-methane hydrocarbons, impurities, and fluids are separated to produce pipeline-quality dry gas in the processing plant.

3.2.6. Pipeline

Pipelines are the primary means of transporting natural gas from gas fields to the consumers; lack of flexibility is a significant challenge. Natural gas transportation involves transmission and distribution, which is a vital part of the gas supply chain and relevant for supply security [62]. Natural gas is transported through pipelines because it is cheaper for transporting across distances of not more than 3,000 miles with larger pipes up to 56 inches for large export quantities of supply. There are three different types of pipes along the gas network system differentiated by their length and diameter, which varies depending on their specific usage. Gathering pipes are used for collecting raw products from the gas field and operate at low pressures and flow rates. They are smaller in diameter than the transmission lines, ranging between 6-20 inches. The diameter of transmission pipelines is usually larger than the gathering or distribution pipes. They are used in transporting large quantities of natural gas across thousands of miles from the processing facility to distribution pipelines or distribution centers known as the city gate stations at high pressure. Most transmission pipelines range in diameter from 20-48 inches. Gas gathering and transmission pipelines form a significant aspect of the gas supply since attention is shifting to stranded reservoirs as a clear majority of gas found in easily accessible locations have already been tapped. To determine the quantity of gas transported at the time (t), factors like the pipe's diameter, length of pipe, temperature, and the pressure exerted by the compressor along the pipeline route are critical.

The distribution pipes are relatively larger than the gathering pipes but smaller than the transmission pipes. They operate at low and medium pressure and consist of a network of small-diameter pipes compared to transmission pipes. There are no compressors, nozzles, or valves along the distribution pipes. Generally, the length and diameter of a pipe influence the gas dynamics. Therefore, for a fixed amount of flow, the difference between pressures at the endpoints is dependent on the pipeline length [66]. The gas pipeline can be thought of as a linear function of inlet pressure to outlet pressure, from point $P1 = P2$, that can only feed consumers along its route. In the forward flow along the transmission pipeline, gas is conveyed from the suppliers (wells, fields, or gathering plant) through the transmission and distribution echelons to the consumers.

3.2.7. City gate station/natural gas company

The natural gas company is usually in charge of operating the city gate station. In this study, the city gate station also represents the gas company. The city gate station is a measuring, pressure monitoring, and reducing package that contains a metering system. The city gate is a point at which a local gas utility receives gas from a transmission system. It supplies gas to the customers in the city at the required consumption pressure of fewer than 300 pounds per square inch (psia) from over several hundreds of psia. The city gate station is found in the distribution echelon of the supply chain network in the downstream and comprises equipment components such as pipes, valves, flanges, and meters.

4. Natural gas supply chain optimization

In meeting natural gas growing demand, studies [53,67–69] have investigated the supply chain to enhance efficiency and overall economic cost reduction through optimization to achieve efficiency in the entire supply chain [70,71]**.** Depending on the researcher**,** the natural gas supply chain analysis is carried out at different levels of the supply echelon because of its complexity [72]. There are relatively few papers that have attempted to optimize the entire natural gas supply chain [53,72] while others studied the supply chain at different levels of the supply network [73,74]. Apart from studying a single echelon, multiple echelons of the natural gas supply chain have studied the production, distribution, and transmission systems [68]. For instance, [44] concentrated on the transportation and the storage levels of the gas network with the objectives to reduce cost and secure the supply of gas by maximizing the deliverability. In addition to transportation and storage, they included gas purchases under uncertain demand. The decision is at the strategic level, while the optimization model starts with the local distribution company. However, for [62], they tried to solve the gas transportation system challenge by focusing on the pipeline and other physical entities along the pipeline like the valves and the compressor. They also investigated line packing issues by using pipelines for short term storage. Other researchers that focused on the gas transportation system with interest in the pipeline include [75,76].

4.1. Mitigating natural gas supply disruption through optimization

There are already existing strategies to mitigate disruption in the natural gas supply chain through optimization such as portfolio diversification, flexible contracts, capacity planning for transportation, and safety stocks [77]. However, only a few studies have modeled the network nodes, which is system-based specifically to mitigate both endogenous and exogenous disruption resulting in the shutdown of a network system. A system-based resilience demonstrates the network's ability to reduce the impact and the period of the deviance from the system performance level in the event of a disruption. The system's absorptive capacity is the degree to which the disturbance impact can be absorbed, and the consequences minimized. This may include the introduction of system redundancy where an alternative pathway is provided for the flow of the supply chain to continue, increase plant and transmission capacity, and reduce shutdown frequency such that the resilience of the supply chain is guaranteed. Therefore, successful optimization provides a robust supply chain that is flexible and reliable to respond swiftly to shortages in supply [25]. Accordingly, system-based optimization ensures that the supply chain nodes respond quickly to external uncertainty like price volatility [78].

In addition to supply chain resilience through optimization, the argument for regional mapping differences in the supply chain of energy sources can help in the learning process of ensuring resilience [79,80]. The study of energy has incorporated theories, concepts, and techniques such that the territorial location of energy becomes a significant component determining the availability, production, and distribution in addition to political, scientific uncertainties, and environmental relationships. The reality of inadequately developed pipeline transportation and gas markets in countries like China, Nigeria, and India, or where technological innovations to enhance resilience are limited in developing countries, strengthens this argument.

Several studies have optimized natural gas transportation, focusing on the gas pipeline [15,44,78] and compressor station [15,75,81]. For instance, a numerical model for natural gas transportation studied the pipeline in a transient state to capture the boundary conditions resulting from demand variation and rupture of the pipeline [82]. Mixed integer nonlinear programming for the gas pipeline extension was presented in [83] for multiple demand scenarios. Also, [84] suggested convex and non-convex formulations targeted at minimizing the energy consumption along with the transmission in an existing pipeline due to pressure drop. A model for controlling the flow of gas in an existing pipeline network was proposed in [85], where the problem of selecting appropriate compressors, valves, and pipes were discussed. The optimization for the transmission network was to achieve expansion for medium- to long-term operations, and strategic decision planning was proposed in [19]. In their design optimization planning, they considered future conditions intending to minimize total cost. However, for compressor unit performance, a simulation model was developed to study the performance of the compressor units by analyzing the pressure and flow parameters under various conditions [76].

The shutdown of compressors or compressor stations during emergencies, periodic maintenance, demand fluctuations during seasonal changes, and supply disruption is inevitable. During an emergency or unplanned shutdown, methane emissions are released into the atmosphere, bringing about recorded natural gas losses to the environment. The venting to the atmosphere of high-pressure gas during the shutdown within the compressor unit and the connected piping between isolation valves is known as ‘blowdown’. Improvement during the shutdown of a gas network node can result in significant savings to the product and the environment. On average, one blowdown vents 15 Mcf/hour of gas to the atmosphere [86]. When the compressor is pressurized, the leakage of gas can be up to 0.45 Mcf/hour. Gas can also be lost to the atmosphere because of depressurization at 1.4 Mcf/hour from a shutdown compressor through leakages from faulty or an improperly sealed isolation valve unit.

There are different methods of reducing gas emissions caused by losses during a shutdown. These methods include keeping the offline compressor pressurized, installing static seals on compressor rod packing, installing ejectors on compressor blowdown vent lines, and connecting vent lines during blowdown to the fuel gas system for recovery**.** Recompression is a current innovative strategy introduced to channel the gas into a neighboring gas pipeline section, especially during maintenance, repair, or pipeline construction work. According to the studies carried out by the Environmental Protection Agency[87], redesigning the blowdown systems such that vents and piping are modified to enable re-routing to the sale line can reduce emission loss. Industry experts carried out an environmental cost-benefit analysis. They found that with the introduction changes in the design of the blowdown system and simple modifications in the operating practices, there can be a significant reduction in losses and emissions during shutdowns. The economic analysis showed higher savings if the compressor is pressurized during the shutdown, and gas is re-routed to a fuel system [88].

4.2. Sustainability in optimization

One of the reasons to mitigate the frequent and prolonged disruption of natural gas network systems is the loss and emission of the environment. Some research works have taken their optimization model further by including sustainability to their research objectives. The multiple objectives of economic, resource, social, and environmental goals in a supply chain is a comprehensive strategy for sustainability [88,89]. For example, the profit optimization goal and customer satisfaction in [90] were expanded with the introduction of environmental and social concerns to the economic goals. Also, [72] introduced environmental effects to minimize economic cost reduction and costs associated with greenhouse emissions.

For most supply chains, economic sustainability is usually of prime importance where the goal of the supply chain optimization is to minimize production, storage, and transportation costs to maximize profit. Resource sustainability deals with fully utilizing infrastructure for optimal results and the least impact on the environment. Social sustainability deals with considering consumers first while planning production. For environmental sustainability, the expectation is for all types of resources utilized efficiently to reduce losses that negatively impact the environment. A truly sustainable energy future ensures loss minimization along the supply chain and lesser carbon footprint [91] such that efficiency through optimization should be achieved without jeopardizing the environment [92].

5. Optimization techniques and modeling for supply chains

The recent industry acceptance of modeling software has encouraged the optimization application in the production and transportation of the supply chain [93]. The fact remains that the supply chains must be constantly optimized if the projected rise in demand must be achieved. In a broad field of study, developing optimization models and solution techniques promotes ways to improve the supply network [69,93]. It is a strategy that ensures resilience in the event of disruption and uncertainty. Optimization bridges the gap between the demand and the supply by providing a buffer through technological innovations at the least cost possible to solve some of the challenging concerns like infrastructural inadequacy, unavailability of resource inputs, cost, demand variation, absence of low-cost feed supply that is stable over a long period, price distortion, and lack of adequate regulatory framework and funding. The general property of an optimization problem is to minimize or maximize an objective function $f(x)$ subject to identifiable constraints X and S, where:

$X (G, I) \leq 0$ (*ii*) Inequality constraint
$S (G, I) \geq 0$ (*iii*) Inequality constraint
$S (G, I) = 0$ (*iv*) Equality constraint

In the modeling of supply chain resilience, simulation [4,26,36,42,82,94] and mathematical models [95] are developed to manage or mitigate disruptions through optimization. Simulation allows one to represent the behavior of the system in the event of a disruption in real-time. For instance, [4] introduced different scenarios using simulation to identify the best supply chain resilience when there is a disturbance to the flow in the supply chain transportation echelon. The researchers in [36] presented a numerical simulation model for multiple echelons of the supply chain to test different mitigation response plans. Similarly, [82] developed a numerical simulation to study extreme conditions in a transient state that may affect the operation of a natural gas pipeline. Researchers for supply chain resilience optimization have also deployed mathematical models. For instance, [95] used a mathematical model to represent the operation, transportation, environmental and delay costs reduction caused by disruptions in the natural gas supply chain. In a more recent work [28], optimization was introduced to an interdependent power-water network to achieve a resilient supply chain using a mathematical modeling approach.

5.1. Optimization solution-based classification

According to [96], the immediate improvement of plant profitability or return on investment is the target of practically all optimization applications. The challenge of selecting an effective optimization technique for a real-life supply chain optimization model in a complex problem requires careful analysis, especially when addressing the production and transportation planning problem. According to [97], the categorization of optimization solution techniques is into four groups, but for this work, only two groups which, include the mathematical modeling and simulation for the supply chain, are presented in Table 4.

To overcome the limitations of mathematical modeling, which is arguably static and unrealistic, and to accommodate a simulation modeling that is projected to be dynamic and realistic by reproducing system behavior, a third proposed group is a hybrid approach that solves the supply chain management problems where there are uncertain occurrences. The study of developing hybrid algorithm mathematical programming and simulation models of a production system was carried out by [98] and extended by Lee and Kim [5] where they showed that in a real-world, the use of the mathematical model is limited because mathematical model ignores realism of the desired phenomena, unlike simulation. Due to the high complexity that affects oil and gas supply chains, and the challenges in developing an accurate mathematical model, [99] suggests the application of the simulation method as a more appropriate technique because of its ability to provide a detailed and dynamic view of the supply chain in the study. Notwithstanding, several researchers apply mathematical models in studying and optimizing supply chains [53,72,75].

Table 4: Optimization Solution Based Classification

S/N	**Mathematical Modeling Method**	**Description**	**Literature reference**
1	Linear programming-based modeling approach (LP)	The objective function *f* is linear subject to linear constraints	[21,100–102]
2	Mixed Integer Linear Programming (MILP)	Includes an additional condition that at least one of the variables can only take on integer values	[68,103,104]
3	Nonlinear Programming Based Modelling Approach (NLP)	The objective function *f* is non-linear subject to linear or non-linear constraints	[74,105]
4	Mixed Integer Nonlinear Programming	The objective function and /or constraints are nonlinear with continuous and discrete variables	[53]
5	Hybrid Programming	This is a combination of both mathematical programming and simulation	[5,98]
6	Fuzzy, Stochastic and Deterministic Mathematical Programming	The fuzzy and stochastic elements deal with problems of uncertainty, while the deterministic element deals with known parameters	[15,20,108,53,62,69,70,72,95,106,107]
S/N	**Simulation Technique**	**Description**	**Literature references**
1	Numerical simulation	This model reproduces system behavior and considers real-time events	[76,99]

6. Concluding remarks and discussion

This paper presents a review of energy supply chain resilience to combat the impact of disruption from the view of optimization. Although the emphasis is on developing a resilient supply chain system for natural gas in the wake of rising global demand for energy as a top priority, the paper also highlights the potential challenges associated with uncertainty on the energy supply chain and its impact on supply chain resilience. While uncertainties from climate change, pandemics, and wars, which are majorly unplanned disruptions, cannot be adequately projected, information gathering and sharing, forecast, and backups are some useful options that can be adopted. A significant uncertainty highlighted is the novel COVID 19 pandemic, which will require time, data, and unbiased information for future mitigation plans and optimization modeling for supply chain resilience. Using optimization to achieve a robust supply chain has proven to be a useful tool for accurate analysis. Currently, studies of various supply chains highlighted indicate the use of backup storage, decentralization, and additional pathway as options for resilience. Also, some studies recommend operation-based strategies for optimization, including the application of a multiple supply strategy, backup suppliers, and additional inventory. However, only a few numbers of research have suggested using a system-based strategy for building a resilient supply chain. Harnessing both system and operation-based strategies can provide a more robust, resilient supply chain. A significant observation is that despite the number of studies on designing and modeling supply chains, only minimal research into supply chain planning connects resilience and optimization. Most of the models reviewed are oriented towards cost minimization, and to a lesser extent, loss reduction and uptime maximization. Current research innovations tend to favor decentralized and microsystems because of the enormous challenges associated with making complex supply chains resilient.

While this paper serves a comprehensive review of supply chain resilience using optimization, some obvious gaps have been identified based on works of literature examined as listed:

- To the researcher's knowledge, there is currently no proposed detailed systematic approach for dealing with shutdowns in a deterministic environment.
- Although uncertainties are likely occurring factors to account for disruption, there is no detailed historical trend analysis to project and estimate potential uncertainties.
- A significant gap also identified is that no research work has provided a detailed strategy for building a system-based resilient supply chain for natural gas. Application of a well-thought-out strategy to other forms of energy, like nitrogen and carbon capture and storage, is likely.
- Finally, there are relatively few papers with multi-objective functions that introduce sustainability as a critical element in their model. Much more is required from proposed models to begin to introduce sustainability as a critical objective function as it relates to system interruptions.

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