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OPTIMISATION OF ENERGY SUPPLY CHAINS CONSIDERING SUSTAINABILITY ASPECTS

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Abstract

The supply chain of energy sources and, in particular, natural gas is prone to endogenous and exogenous disruptions that affect the system's operational performance and flow capacity, thereby contributing to greenhouse gases (GHG) through methane (CH_4) emissions. Although there are operational strategies to improve the gas supply chain, the need for resilience-driven optimisation that provides a system-based workflow to mitigate continuous and prolonged disruptions in the midstream remains crucial. This study focuses on developing a novel optimisation model that investigates the potential of a complementary design in the natural gas supply chain as a mitigation approach, enhancing throughput delivery without disconnections, and exploring the potential retrofit benefits of an existing natural gas supply chain infrastructure. To achieve this, optimisation in the supply chain's transmission echelon is deployed to increase flexibility capacity, reduce gas losses, and minimise emissions. In this study, a lateral relief pipeline in the transmission node is proposed as an alternative pathway for gas flow to increase the resilience of the supply chain. This proposed strategy transmits excess trapped gas between inlet and outlet nodes during plant shutdowns within operational and contractual constraints. This redundancy compensates for downtime and pressure drop caused by shutdowns of system nodes during disruptions. The objective of the optimisation problem is to maximise throughput through flow flexibility and minimise carbon dioxide (CO_2) emissions through a reduction in gas losses. Different scenarios are introduced to achieve the objective function optimum. Firstly, the baseline scenario (BS) of the system's status is analysed under normal conditions to identify the flow rate gap. Then the disruption scenario (DS) is introduced where the impact of the lateral relief pipeline to mitigate unplanned shutdowns is analysed by using defined parameters in a steady state (SS). With a fixed shutdown period, the variation in plant node performance is examined at different flow rates. Lastly, in a transient state (TS), the pressure variation between the inlet and the outlet nodes in the mainline and when the relief pipeline node is opened is investigated. All scenarios affect the supply chain's overall performance; therefore, the resulting flow rates are compared for optimum decision making. A multi-stream, multi-period, single-product transmission model to satisfy consumer demand within a given time frame is developed for the simulation, formulated as a mixed-integer linear programming (MILP) model, and applied within an optimisation framework where interruptions to the supply chain are studied to optimise the strategic planning problem. The optimisation procedure is formulated in a deterministic environment, and the model is run using General Algebraic Modelling System (GAMS) 26.14 with the CPLEX solver 12 in an intel ® core ™ i7 and a zero-optimality gap. Data collected from gas companies in the case study country are analysed and used to forecast and calculate the gas flow rate and the required capacity to meet growing demand. The data accessed enhance the applicability of the proposed model. Also, the interactions between the nodes in the supply chain are adjusted to mitigate interruptions and increase overall efficiency. Furthermore, an economic analysis of the proposed complementary design is carried out to ascertain possible trade-offs between costs and resilience. Finally, a sensitivity analysis is conducted to assess the impact of key parameters on the overall model's prediction.

Keywords— Energy, Natural gas, Supply chain, Emission, Mitigation, Sustainability, Relief pipeline, Optimisation, Mixed integer linear programming, Resilience.

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Definitions/Abbreviations

ABEX	Abandonment cost
AF	Additional flowline
BCM	Billion cubic meter
BS	Baseline scenario
BTU	British thermal unit
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CH_4	Methane
CNGA	California Natural Gas Association
CO_2	Carbon dioxide
CV	Calorific value
DS	Disruption scenario
EPP	Export parity netback gas price
FINEX	Financial expenditure
FFE	Fundamental Flow equation
G	Gas gravity
GAMS	General Algebraic Modelling System
GFE	General Flow Equation
GHG	greenhouse gas
GHV	Gross heating value
GWP	Global warming potential
IPCC	The Intergovernmental Panel on Climate Change
KM	Kilometre
LES	Loss and emission savings
LNG	Liquefied natural gas
LP	Linear programming
MCF	Million cubic feet
MIP/MILP	Mixed integer programming/ Mixed integer linear programming

MINLP	Mixed integer non-linear programming
MMSCFD	Million standard cubic feet per day
MSCF	Thousand standard cubic feet
MCF	Thousand cubic feet
N_2	Nitrogen
NHV	Net heating value
NLP	Nonlinear programming
NPV	Net present value
OPEX	Operation and maintenance cost and
OS	Operating status
PVF	processing node volume flexibility
PSI	Pound per square inch
Q	Gas flow rate
REC_S	Reduced emission completions
RS	Resilient state
SNG	Synthetic natural gas
SS	Steady state
SVF	Supply node volume flexibility
TCF	trillion cubic feet
TS	Transient state
TVF	transmission node volume flexibility
TWH	Terawatt-hour
USCS	U.S. Customary System
WACC	Weighted average cost of capital
Z	Compressibility factor

Chapter 1

Introduction

1.1 The energy supply chain

The energy supply chain is an integrated network of facilities that vary significantly in size, complexity, and scale [1–3]. It characterises a synchronised series of interrelated business processes, which includes the forward flow of raw and finished products and the backward flow of information. Each component of the energy supply chain are essential in shaping the entire supply chain system, and managing these components is challenging. Energy availability and affordability in both developed and developing economies are widely considered vital for economic and societal growth [4–6]. The success of other supply chain systems depends largely on access to energy, which is guaranteed when the supply chain operates adequately. Energy carriers are generally grouped into two forms depending on the view of the researcher. The opinion of the majority is that fossil fuels are predominantly oil, nuclear, coal, and natural gas, while renewable fuels include hydropower, solar, wind, biomass, and geothermal. However, a different opinion is found in Asif and Muneer [4] where nuclear is mentioned as the third form of energy.

The increase in energy consumption requires continuous improvement of all forms of energy supply chains. In a recent British Petroleum [7] report, the total global energy consumption as indicated increased by 2.9 percent in 2018 almost doubling the 10-year average, with growth in natural gas accounting for 43 percent of total global energy increase. For instance, though natural gas production in the UK decreased by 3.3 percent in 2018 compared with 2017 to 450 terawatt-hours (TWh), net import rose by 11 percent in 2018 compared with 2017 making a 0.9 percent increase in total gas demand in 2018 compared with 2017 and an increase of 3.8 percent in total consumption for the same period [8]. Experts suggest that energy consumption growth will double by 2050 compared to 2020.

As the global scene continues to face demand growth triggered by a change in economic and population size, the need to meet the rising demand while reducing CO_2 emissions equivalent continues to gain relevance (see Fig.1). The challenge identified with energy consumption growth is the potential increase in environmental pollution through the continuous emission of greenhouse gases (GHGs). This suggests that the acceleration of human and system activities will continuously impact the ecosystem adversely. To assuage the impact, the Intergovernmental Panel on Climate Change (IPCC) report on global warming recommends that by 2030, CO_2 emission should be halved or maintained below the 1.5°C threshold [9]. However, the report in British Petroleum [10] shows that CO_2 emissions from energy use will rise by roughly ten percent in 2040, except the alternative rapid transition takes effect.

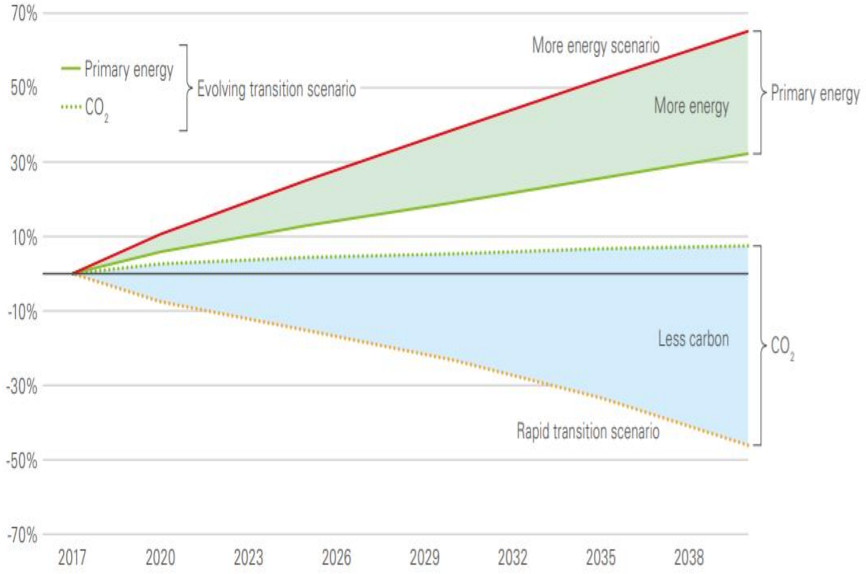


Figure 1: Global primary energy demand and CO_2 emission by 2040 [10]

Two critical success factors for the energy supply chain are the provision of sustainable energy for economic and social development and the reduction of adverse impacts on the global climate. Sustainable energy includes energy sources with little or no damaging impact to the environment, which have the potential to replenish within human lifetime. The introduction of efficient technologies arguably produces fewer pollutants in the energy supply chain according to Pollitt [11]. An obvious challenge is that most energy supply chains comprise complex connected physical structures that are vulnerable to external interferences. Optimising the energy supply chain produces the best solution among all feasible solutions to meet this increasing energy demand. Perhaps at such a time when society faces a more significant challenge to guarantee robust energy supply chain systems for natural gas domestication and gas-powered projects, optimisation becomes imperative.

The continuous functionality of the energy supply chain is generally affected by numerous challenges that trigger an increase in its complexity and vulnerability that sometimes results in shutdowns of nodes [12]. These challenges result in interruptions or disruptions that affect the functionality of the supply chain. The energy supply chain functionality is impacted by several challenges which increase the complexity and vulnerability. Infrastructure failure, routine or emergency shutdowns, conflicts, human attacks, sabotage, vandalism, environmental disasters, theft, demand fluctuations, inventory shortfalls, inefficient supply capacity, and political cataclysms are some of the factors that cause disruptions [13]. These disruptions affect the throughput of the system. To withstand the effect of these disruptions, steps are taken by the operators to ensure the resilience of the energy supply chain. Earlier research shows that a resilient system will respond swiftly to interference and return the system to its original or an even more desirable state before the disruption (see section 2.1). Although disruptions are intrinsic attributes of energy systems, the need to identify root causes that can cause prolonged shutdowns is important.

The disruptions mentioned above have been classified primarily as external and internal factors. Exogenous or unplanned disruption are triggered by external factors beyond the control of the plant operators and field engineers. Dealing with these exogenous disruptions constitutes a significant drawback in supply chain optimisation. The impact is usually severe when they occur, thus inducing a risk to the supply chain system. Some of the consequences of unplanned shutdowns include the high cost of failure, operational downtime, and environmental effects. On the other hand, endogenous disruptions known to be triggered internally makes it easier for operators to control [14]. Based on the research of Kleindorfer and Saad [14], it can be inferred that the resultant shutdown from system interruption is caused by three factors: emergency-external and out of control, routine maintenance-internal and out of control, and demand fluctuation-external but controlled.

1.2 A strategic player in the energy mix

Several researchers have investigated individual fuel sources used for energy generation and their particular supply chains to improve the energy supply chain. Natural gas plays a significant role in the energy mix for gas power plants, industrial and domestic consumption, and low carbon technologies. Projections of future energy mix suggest high shares of NG and renewables comprising about 85% of total energy growth [10]. According to Mokhatab [15], the projected growth in natural gas has seen a steady increase in gas demand for gas-fired power generating plants, which far outweighs its supply. The role that gas plays in the short and long term must be given full attention to achieve the energy trilemma, comprising demand security, affordability, and sustainability.

This research concentrates on natural gas as a strategic player in the energy mix and a reliable energy fuel source that bridges the gap between conventional and renewable sources [16,17]. Some researchers have explained the relevance of natural gas in terms of its general use, and relatively low greenhouse impact and its likely further increase in the global primary energy mix for different users due to the decline of coal in power generation [18,19]. While the demand for natural gas continues to increase (see Fig. 2), the glaring challenge is applying an efficient way of meeting changing gas demand profiles with the most effective supply chain procedure. As shown in Fig. 3, the transition to lower-carbon energy continues with natural gas and renewables gaining an upward trend compared to other energy sources and constituting about 85 percent of total energy growth [10]. Accordingly, in addition to increasing demand for renewable sources, natural gas is a critical element in the transition to a cleaner, more affordable, and secure source of energy [20,21].

Furthermore, Ríos-Mercado and Borraz-Sánchez; Economides and Wood [22,23] argue that natural gas benefits from reduced capital cost and vast deposits of proven and unexploited reserves. Therefore, it is an essential global energy source. Natural gas is arguably the cleanest and most hydrogen-rich of all hydrocarbon energy sources, combined with its high energy conversion efficiencies for power generation [23]. Sustainable industrialisations seek affordable and cleaner sources of energy. Like other energy supply chains, the supply of natural gas can be constrained by interruptions on the network node caused by planned or unplanned events. Typically, when there are planned interruptions, strategies are put in place to absorb the possible inconvenience, but this is unlikely during unplanned interruptions. The competitiveness of renewables like wind and solar is gaining ground as experts continue to provide cost minimisation and solution technologies for storage, which has hitherto limited the demand growth. For natural gas to continue to maintain its relevance as a cleaner source of fossil fuel growth, operators must reduce shortages and losses, maintain its future cost, and provide sufficient profit for investors.

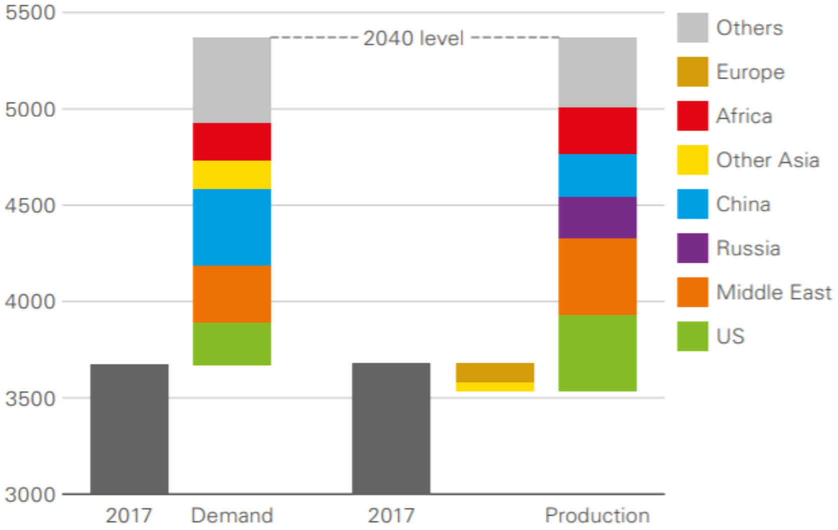


Figure 2: Global gas demand and production in Bcm [10]

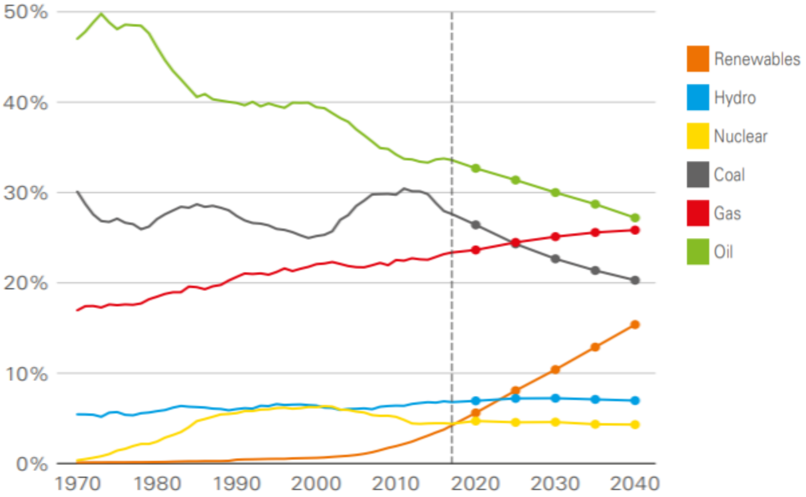


Figure 3: Primary energy mix from 1970 – 2040 [10]

1.3 Origin of Natural Gas

The previous section established the importance of natural gas as an energy source. It is therefore relevant to provide a brief overview of its origin and classification in this section. Natural gas is a proven occurring hydrocarbon mixture found underground at elevated conditions of pressure and temperature. Therefore, it is a naturally occurring gaseous fossil found in gas-bearing formations [24]. For several decades, the consumption of natural gas has primarily been for fuel, power generation, chemical feedstocks, industrial fuel, and petrochemical feedstocks. However, the use of natural gas did not certainly match its discovery in most countries. Although the discovery of natural gas dates to ancient times in the Middle East, the practical use pre-dates to the Chinese 2500 years ago. However, the discovery of natural gas in England was in 1615 before its discovery in other parts of Europe.

Unlike England, research shows that natural gas discovery in the United States was in West Virginia in 1815 during the digging of a salt-brine well in Charleston [15]. The shock in crude oil production in the late 1960s gave rise to alternatives and a steady state growth for gas. The need to embrace the exclusive use of gas for lighting at localised levels was in the early twentieth century. Before the current broad global utilisation, natural gas was typically used for lighting in the 19th century [25]. The cause was the lack of adequate transportation infrastructure to export natural gas in large quantities. The progress in pipeline transportation was visible only after World War II with advancements in pipeline networks [25].

In Nigeria, the 19th century witnessed the discovery of natural gas. Oil and gas production in 1958 witnessed local gas consumption for industrial use, which commenced in 1963. However, in the early 1970s, gas production increased, and by 1979 production was recorded at approximately 2.7bscfd, growing to about 8.2bscfd in 2015 [26]. Natural gas is known to occur in deep reservoirs associated with crude oil production or non-associated with little or no crude. Currently, the natural gas in Nigeria is produced and exported majorly as liquefied natural gas (LNG) to foreign markets but supplied to the domestic market in smaller quantities. These vast gas reserves are categorised as associated natural gas (crude oil trapped along with natural gas) or non-associated natural gas (natural gas in a reservoir with little or no crude oil) with a significant volume found as associated gas in deeper reservoirs [26].

- **Associated natural gas**: The associated natural gas usually occurs as free gas in a petroleum reservoir or as a solution gas in the oil reservoir. It is said to be more assertive in molecular weight hydrocarbon constituents and thinner in methane [27]. Crude oil is often produced with some low-boiling hydrocarbon constituents, which are of little or no value at the point of drilling to the oil exploration company and therefore emitted. In oil exploration, the introduction of reservoir management protocols is if the target is to reduce the amount of associated gas produced. Fig. 4 is a sample of an associated gas reservoir.

- N**on-associated natural gas**: Unlike associated gas, the non-associated gas occurs from a geological formation with little or no crude oil, and it is usually higher in methane and thinner in molecular weight hydrocarbons [27]. Sometimes, it contains non-hydrocarbon gasses, which are removed during processing to form dry gas. The current industry focus is on non-associated gas production resulting in more gas infrastructural development.

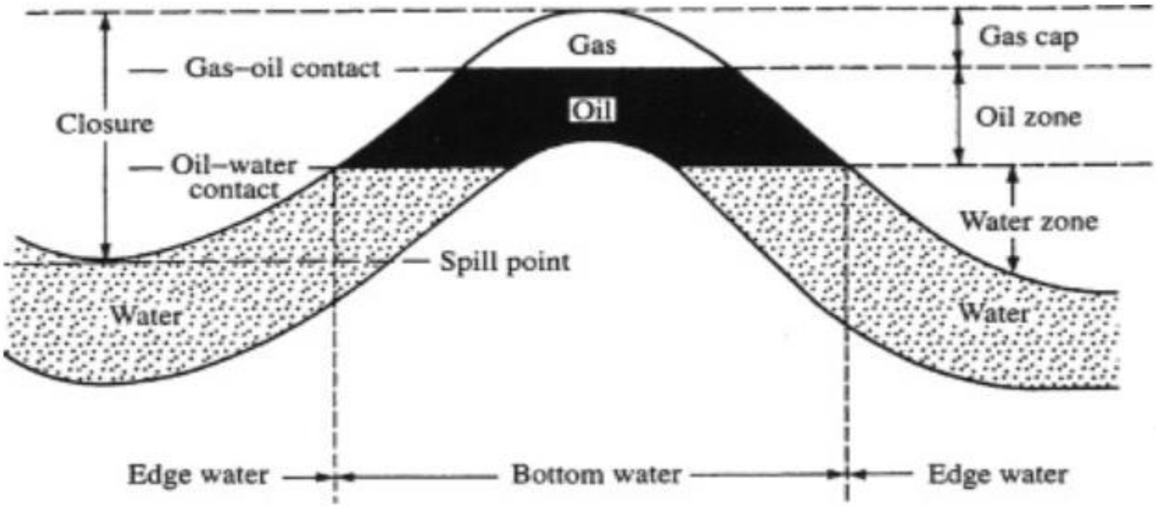


Figure 4: Associated gas reservoir [25]

1.4 Carbon emissions reality

Greater awareness for environmental protection through reducing CO_2 emissions has gained more attention as climate change continues to rise. The latest report released by IPCC on 'Global warming of 1.5°C confirms the need to cut CO_2 emissions by limiting warming to 1.5ºC by 2030' [9]. The need for an unprecedented low carbon transition in the energy sector will help global warming mitigation coupled with energy decarbonization goals. According to Tabkhi et al. [28], the drastic changes in energy policies align towards tackling present-day urgent environmental challenges, such as controlling GHG releases.

Natural gas generally has low carbon composition and a low carbon footprint compared to other fossil fuels. However, on a weight basis, the major greenhouse gas is CH_4, which is its primary component, which is 23-25 times more radiatively potent than CO_2, based on a 100-year interval Global Warming Potential (GWP) posing a challenge if emitted [29,30]. It is said to be the top producer of anthropogenic GHG footprint after CO_2, with a higher capacity of trapping atmospheric heat. Methane emissions are either vented, fugitive, or through combustion, and these types of emission can occur during start-up, normal operations, maintenance, upset, and mishap activities [31]. Therefore, GHG emissions can originate from both planned and unplanned activities. Venting involves controlled release of CH_4 into the atmosphere, fugitive emission occurs during the production and transmission activities in the supply chain whereas, combustion is the burning of natural gas.

In comparison to the impact of CO_2, a study conducted in 1996 converted CH_4 into CO_2-eq equivalent using the Global Warming Potential (GWP) on a scale value of 34 and 6.5 with a corresponding time range of 50 to 500 years, shows a lower impact of methane compared to CO_2 on global warming [31]. However, efficient gas utilisation ensures the control of potential methane emissions by applying green completions, also known as reduced emission completions (RECs). In well completions, engineers ensure prompt detection and repairs, use of dry seals, and vapour recovery units. These, amongst others, are control mechanisms put in place. Several opportunities to reduce GHG emissions from natural gas extraction, delivery, and power production have also been recognised [32].

Although efficient energy utilisation is in place for industrialised nations, the reverse is the case for emerging countries. For instance, in Nigeria, the annual cost of continuous gas flare is put at US$ 2.5 million, with a release of about 16 million tons of CO_2 into the atmosphere, causing increasing global warming with only about $0.03/Mscf penalty cost for associated gas flared. Around 45.8 billion kilowatts of heat is emitted into the atmosphere based on expert calculation from a daily flaring of 1.8 billion cubic feet of gas [26]. However, the IEA report [33] argues that CO_2 will be intently cut in industrialised and emerging economies if natural gas is efficiently utilised to meet the growing demand and reduce emissions and losses. Although CO_2 emissions related to energy use rose by at least 50 percent from 1990 to 2014, the move towards natural gas and other related less carbon-concentrated energy fuels will enable global energy-related CO_2 emissions to peak by 2040 [34].

The benefit of processed natural gas utilisation is that it contains a less intricate chemical structure and reduced volumes of impurities coupled with secured processes operations, predominantly with fewer chances of release. Notwithstanding, the shutdown of network nodes like compressors or compressor stations during emergencies, periodic maintenance, demand fluctuations, seasonal changes, and supply disruption is inevitable, causing a gas loss in the supply chain. The occurrence of any of these events listed produces emissions through leakages or venting of the high-pressured gas left in the compressor.

The diagram in Fig. 5 demonstrates the resulting emission from disruption on the gas supply network. During the 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’ [30]. An improvement during the shutdown of the gas network node can result in significant savings to the product and the environment. Research shows that, on average, one blowdown vents 15Mcf/hour of gas to the atmosphere [35]. When the compressor is pressurized, the leakage of gas can be up to 0.45Mcf/hour. Gas can also be lost to the atmosphere because of depressurization at 1.4Mcf/hour from a shutdown compressor through leakages from faulty or an improperly sealed isolation valve unit.

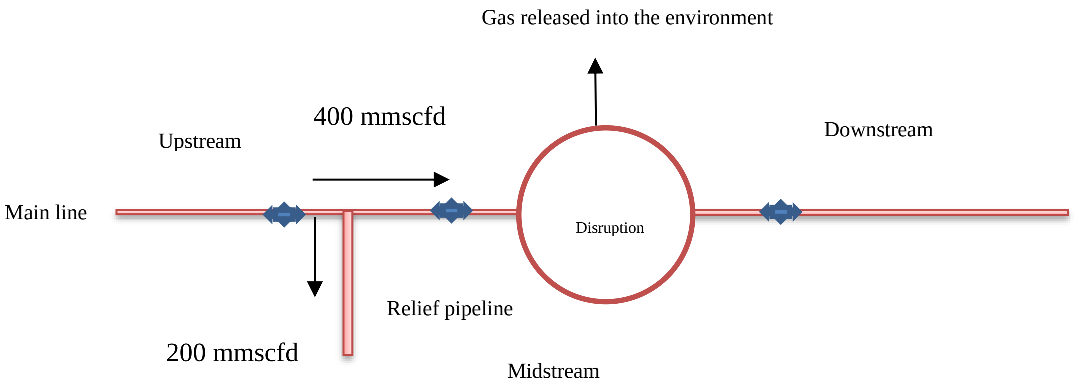


Figure 5: Mainline with relief pipeline

Every shutdown of a natural gas network node results in a subsequent start-up and a resultant loss. According to industry experts, the number of shutdowns of nodes like the compressor station must be reduced to achieve natural gas loss reduction. Different methods of reducing gas emissions caused by losses during a shutdown exist as proposed by industry experts. 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.

In addition to the methods listed above, recompression is currently an innovative strategy introduced to channel trapped gas into a neighbouring gas pipeline section, especially during maintenance, repair, or pipeline construction work. These methods are improvements to the gas emissions during shutdowns; however, there is still the need for better improvement with the introduction of an additional design of the gas workflow to allow for contingencies without disconnections. According to the studies carried out by the Environmental Protection Agency [36], redesigning the blowdown systems such that the emergency shutdown vents and piping is modified to enable re-routing to the sale line can reduce emission loss. Adopting measures to avoid blowdown of compressors during the shutdown can result in fewer natural gas volume releases, a lower rate of leaks, and utilisation of methane by fuel systems otherwise flared such that fuel cost is reduced.

1.5 Problem description

The performance of the production, transmission and distribution levels of the natural gas supply chain is mostly constrained by the impact and effect of interruptions to the supply nodes. Whether the disruption time is within acceptable limits is left for the engineers to decide. This work investigates the challenges of the natural gas supply chain caused by unplanned interruptions. Some of the identified challenges include the shortage of supplies from gas fields, prolonged compressor and pipeline shutdown, and over-costed infrastructure. These challenges can affect the production and consumption process. Although the physical infrastructure, telecommunications, business environment, and project cost of the entire supply chain needs improvement, this work focuses on the physical infrastructure optimisation of the gas transmission problem. Based on the identified challenges, the work presents a proposed optimisation framework strategy for an additional gas workflow design to mitigate potential disruptions.

The studied problem introduces different scenarios in an emergency shutdown of a plant node. Excess trapped gas in the mainline feeding into the compressor station is typically emitted when there is an unhindered flow of gas in the pipeline from the upstream echelon until the inlet valve is completely closed, posing a threat to the environment. Often, this pressurised gas is discharged through a release valve to avoid a fire outbreak. The immediate challenge identified in this work is to guarantee the resilience of an existing supply chain to reduce losses through maximisation of throughput and downtime reduction. Based on the definition of resilience from literature as provided in Carvalho and Machado [37], it can be argued that resilience of the studied supply chain is the ability of the supply chain system to return to its original state of throughput delivery or to a more desirable state where throughput is maximised, even after experiencing a disruption.

The resilience of the gas network is evaluated when disruption occurs to a system node resulting in the closure of a node segment. Each component of the supply chain is represented as a node, including the suppliers and the consumers. The case study for the problem investigated is presented in chapter three. The actual performance of the gas network in an operational state for the problem is identified; the optimisation model is developed and applied to study the disruption in the gas supply transmission network. Based on the problem description, the objective function of the optimisation model is to maximise the supply chain resilience such that the throughput is increased resulting in loss reduction during a plant shutdown at little or no cost tradeoff. Therefore, the following research questions are of interest:

1. What is the best resilience strategy to be adopted for an interconnected process system that is susceptible to disruptions?
2. What possible parameters can affect the flow rate in the proposed relief pipeline?
3. What is the most appropriate and sustainable strategy to tackle exogeneous disruption in the energy supply chain?
4. What possible emission loss savings can be achieved if throughput is increased?
5. What is the impact of an additional design on the natural gas workflow that allows for contingencies without disconnections?

1.6 Research aims and objectives

This research proposes a systematic approach for the midstream process optimisation of a natural gas supply chain that deals with emergency shutdowns by utilising data collection and analysis in both static and transient states. This work analyses the gas supply chain to optimise resilience for throughput maximisation and minimise associated CO_2 or CO2-eq emissions. This optimisation process aims to meet both the resilience and sustainability criteria of the model. Having an agile supply chain process and manoeuvring around the complexity of the system to meet estimated throughput is a critical success factor for this research. It is expected that the results and findings extracted from chapters five and six will align with the overall aim of this research. The supply chain planning horizon adopted for this work is 30 months divided into monthly time intervals for evaluation based on the available data collected from the industry. To achieve the aim of this research project, below are listed the following objectives.

- Assemble a state-of-the-art literature review on energy supply chain resilience through optimisation. This review presented in chapter two provides the scope for this study.
- Develop and apply a novel optimisation model to optimise a natural gas supply chain system in terms of its resilience.
- To evaluate the impact of the lateral relief pipeline as a proposed loss mitigation strategy on the natural gas supply chain.
- To evaluate mitigation strategy impact on the natural gas supply chain.
- To propose an additional gas workflow design to allow for contingencies without disconnections that allow for minimal loss and continuous flow.
- To estimate the profitability of the investment within a time frame through a cost estimation model.
- To evaluate emissions savings after optimisation.
- To assess the impact of critical parameters on the optimisation results by performing a sensitivity analysis study.

1.7 Methodology

The methodological structure adopted for this research problem, as illustrated in Fig. 6, demonstrates the procedure taken to analyse the research problem. To achieve a near accurate and realistically feasible result, this research identifies the use of an analytical MILP approach that requires the allocation of appropriate parameters like pressure, capacity, online and offline period, and mass flow rate at the critical nodes of interest and bounds for operating flow and shutdowns. This mathematical approach provides versatility and applicability to large and complex problems such as system process integration by exhibiting global optimum with well-defined solutions. The focus of the optimisation analysis is to achieve a realistically achievable result.

The methodology adopted is to develop a MILP mathematical modelling algorithm that considers emergency shutdowns and introduces a relief pipeline using the concept of redundancy. The model adopted analyses the system by looking at the relationship of the individual components to achieve a defined objective function. The methodology also considers the fundamental equation of gas flow and the corresponding assumptions for transmission nodes. Different scenarios are introduced in the methodological framework, starting with the baseline for analysis, and then the compressor performance is analysed. The model developed is applied to the defined problem in different scenarios, first in the steady state when there is a shutdown, then the relief pipeline as a resilience strategy that operates only for a specified period during interruptions and reopening of the mainline valve.

In the steady state, the system is programmed to record no variation in pressure and temperature. The model is also applied to optimise the resilience performance of the gas supply chain in a transient state. Using the best pressure and flow rate required to give the best optimality value is estimated using a time-series that represents a series of data points within the planning horizon. The throughputs of all scenarios are analysed for optimum performance. Therefore, the savings on gas loss in terms of CO_2-eq were extrapolated; finally, with the calculation and analysis of comprehensive economic cost estimation for the additional pathway, ultimate decision making becomes possible.

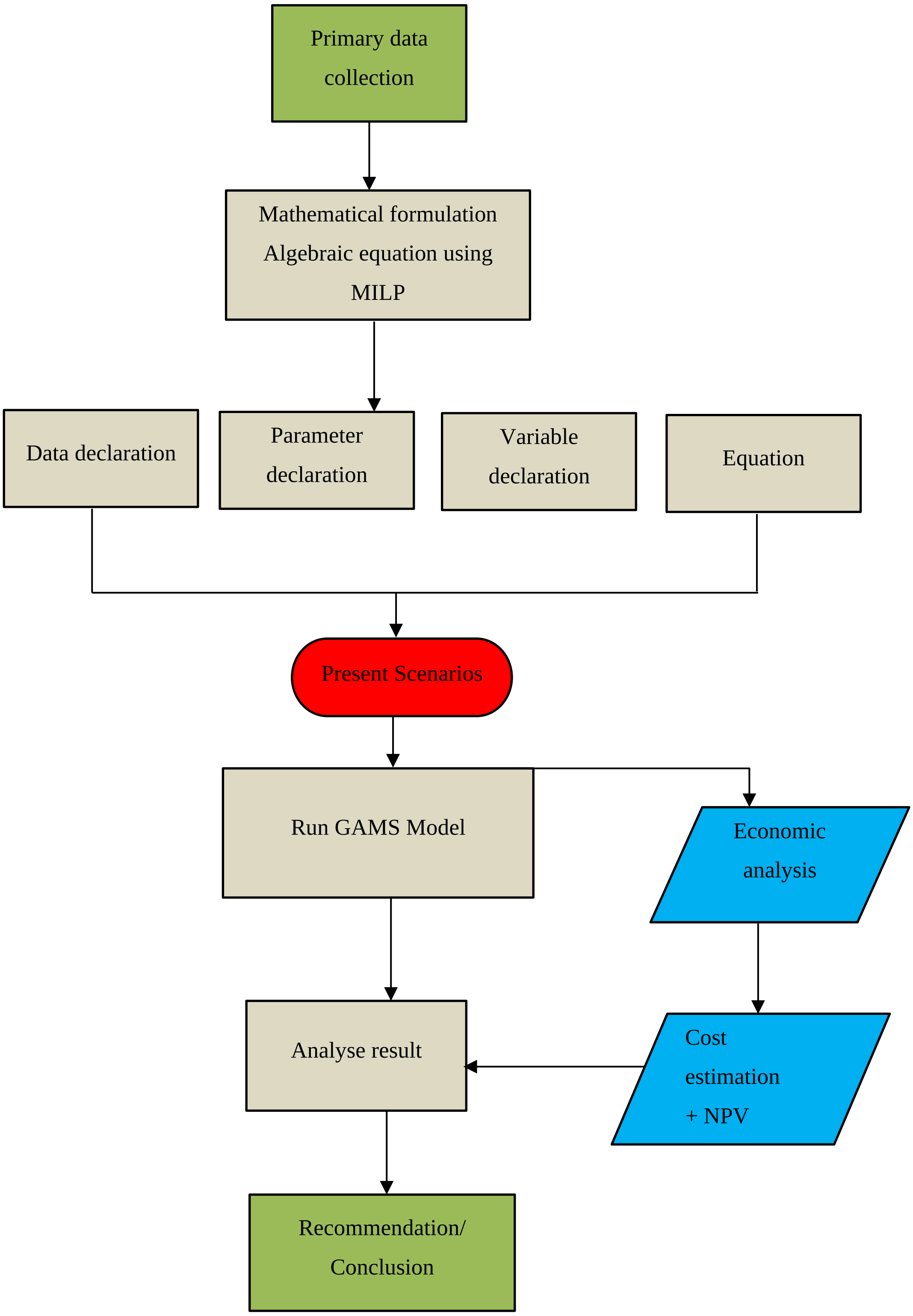


Figure 6: Methodological composition of this research

1.8 Thesis overview

Chapter two presents a literature review on resilience, optimisation, and sustainability as they positively affect the natural gas supply chain. Reviewing available scientific research work provides a better understanding of applying optimisation to improve the gas supply chain resilience in the face of disruptions and uncertainties. With the lessons learned from existing works of literature and the right tools applied, a mitigation approach that introduces an additional design of the natural gas workflow to allow for contingencies is proposed. Furthermore, in this chapter, sustainability is explained as an economic, resource, social, and environmental objective. This chapter also presents the description of significant nodes in the gas network, the challenges that are likely to affect the functionality and increases the natural gas supply chain vulnerability, and the possible occurrence of these challenges. Different disruption strategies suggested for gas supply chain systems are also emphasised. Finally, the most appropriate strategy for the research is identified based on exogenous and unplanned disruptions.

Chapter three introduces the analytical model applied in the research, the relevance of the gas quality, and how this may affect the flow rate in the pipeline because of impurities in the gas composition. The weighted calorific value (CV) of the gas mixtures ensures the quality of the gas from a mixture of different material input flow gets an optimum CV within the required range. Finally, the case study for this research is presented in chapter three.

Chapter four presents the formulation of the optimisation model, which includes the objective function, main parameters, decision variables, and relevant constraints used in the model. The relevance of the proposed workflow based on the activities that occur during plant shutdowns is explained. A multi-period, single product, transmission model to satisfy consumer demand within a given time is analysed. However, in the model formulation are all nodes in the gas network. Some major parameters considered in the proposed workflow include the capacity of the nodes, the flow rate of the gas, inlet-outlet pressure and temperature in the pipeline, proportional and cumulative capacity for expansion, the distance between inlet node and outlet node (pipeline length), and the pipeline diameter (size).

Chapter five focuses on the steady state of the problem in a deterministic environment such that the problem parameters display little or no uncertainties. Five different scenarios are analysed in this chapter. This chapter presents a detailed analysis and application of the model to the steady state case study. Once formulated, the GAMS/CPLEX solver is used to run the simulation. When the number of plants in each node used for the optimisation and the delivery capacity of the existing infrastructure is known, then the required capacity to meet growing demand is calculated. The interactions between the nodes in the supply chain are adjusted to mitigate potential risks associated with disruption and increase efficiency.

Chapter six analyses two additional scenarios in the transient state from the shutdown of the plant node k to the opening of the relief pipeline. The transient state is introduced to typify the behaviour of the gas flow when the inlet and outlet valves of the disrupted node is activated and when the proposed workflow is operating. The pressure variation under the transient condition for the mainline and the relief pipeline is determined. However, the transient condition is restricted to the mainstream pipeline and the alternative pathway transmission nodes. The impact on the flow rate is compared with the steady state condition.

Chapter seven analyses the benefits of resilience to the natural gas supply chain and the environment by calculating savings on emission after the optimisation. Sensitivity analysis is also conducted on key identified parameters in this chapter.

Chapter eight explores the economic analysis of the proposed pathway by introducing a comprehensive cost estimation and control. The Incremental cost incurred is calculated as the engineering cost. The cost is calculated on the relief pipeline node both for existing and new gas network projects and help to make an economic decision. The cost analysis is made on these two different independent projects. Based on the calculated net present value (NPV), decision-makers can decide if the optimised workflow is worthwhile.

Chapter nine discusses the significance of scientific contributions and conclusions. This chapter also highlights the relevance of the research, recommendations for further study, and the limitations to the research.

Chapter 2

Review of Supply Chain Resilience, Optimisation, and Sustainability

This chapter is based on the following peer-reviewed journal article:

- Emenike SN, Falcone G. A review on energy supply chain resilience through optimization. Renew Sustainable Energy Rev 2020;134. doi:https://doi-org.ezproxy.lib.gla.ac.uk/10.1016/j.rser.2020.110088.

2.1 Supply chain resilience

Resilience is a concept that denotes both strength and flexibility, and it is adopted generally in all disciplines of research [38]. The resilience of a supply chain network depends on its ability to swiftly react to interference and return to its original or a more desirable state before the disruption [12,39,40]. Resilience is an index that measures the capacity to sustain a level of functionality or performance for a given infrastructure over a given period [41]. The performance measurement of resilience is in terms of economic losses or gains, casualties, external impact, and recovery time. A supply chain network is said to be resilient if it can overcome stress or system failure. Building a resilient supply chain ensures supply and demand equilibrium or at least minimise shortfalls in supply.

Due to the existing extensive research work, this study does not intend to cover all literature on the subject matter but will identify only relevant literature for this research work. The scope of resilience as an area of research covers technical, economic, environmental, social, and policy aspects. An increasing societal pressure on business sectors to meet the challenges of ensuring resilient supply chain systems bring about the need to optimise existing networks for cost reduction, system flexibility, delivery uptime, reliability, and efficiency.

Resilience is a positive outcome with better performance shown by higher numbers [42]. Resources are needed to restore the system performance, which involves the capacity of a system to reduce, absorb, or recover from a shock caused by abrupt disruption [38]. Researchers assert that resilience is connected to extreme events occurring during the life cycle of infrastructures [43]. Based on open literature, the resilient supply chain studied or developed are either infrastructure based [12,38,40] or operational based [44,45]. For instance, in Schmitt and Singh [45], infrastructure-based resilient supply chain, inventory, and backup systems were analysed, while Todini [46] introduced redundancy to increase the pipe infrastructure reliability when disruption occurs. 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 Burke, Carrillo, and Vakharia [47] while the gas contracts, fuel consumption, and on/off-grid operation of the plant generators were modelled for power system resilience [48].

The complexity of a supply chain affects its resilience according to Christopher and Peck [39]. The argument that complex supply chains are less resilient than smaller-scale technologies indicates that complex supply chains have significant infrastructure innovation barriers and faced with several blockages that are difficult to resolve. For every system, an infinite number of disruptions can be identified, making it difficult to study the system's resilience regarding all possible disruptions to the system [42].

Relevant studies on the various resilience strategies adopted range from supply network design like looped water distribution and natural gas [41,46]. Others include a decentralised model of congestion control in a natural gas network during conflicts [49]. Managing the recovery of the integrated and interdependent network such as electrical power, natural gas, water distribution, and telecommunications have also been studied in Moslehi and Reddy; Sayed, Wang, and Bi; Almoghathawi, Barker, and Albert; Lin and Bie [41,47,49,50] and resilience resources in Hussain, Bui, and Kim; Jufri, Widiputra, and Jung [44,52] like microgrids and power grids for power systems. Despite the number of research on designing and modelling a resilient supply chain, connecting resilience and supply chain optimisation related to natural gas is rare in supply chain planning literature. A useful reference where optimisation is linked with resilience is found in Todini [46]. The researcher used the resilience concept to develop a heuristic optimisation for a water distribution looped network. However, the work was based on network design under pre-operating activity. Generally, optimisation is introduced to attain efficiency in the supply line [53,54]. Supply chain development optimises production, distribution, and storage of a secure system to respond rapidly to demand forecasts throughout a short to the medium-term period [55].

2.1.1 Resilience strategies

Reviewing available scientific research provides a better understanding of implemented strategies for supply chain. In recent times, various researchers have implemented various strategies to achieve resilience irrespective of the product type. Mitigation, recovery, and passive acceptance are three disruption management strategies adopted for any supply chain type [56]. According to Moslehi and Reddy [42], mitigation entails preparedness before disruption, the recovery entails action taken after the disruption, whereas with passive, no action is expected. For this work, the mitigation strategy has been identified as most suitable because exposure to disruption is estimated and anticipatory actions taken to lessen the risks.

2.1.2 Assessment of resilience

In accessing the resilience, the three strategies adopted depend on the type of supply chain and what the operators intend to achieve. All three types are reliant on the cost and what is of priority to the firm. In this subsection, these three strategies are explained further in detail.

Mitigation strategy

The mitigation strategy involves actions taken in advance to plan for disruption occurrence. Some of the strategies adopted over the years 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. The mentioned approaches are supported by the explicit target of the

UNSDGs on resilience regarding the development of reliable, sustainable, and reliant infrastructure [57]. Regarding the emission of greenhouse gases from fossil fuel combustion, agriculture and cement production, mitigation serves a pointer to reduce the rate of climate change through the management of its contributing factors [58].

In Carvalho et al. [59], the researchers proposed using a decentralized controller for congestion control during a disruption in the natural gas pipeline network that distributes the available network capacity to each node to maintain network throughput. They suggested iterative allocation of path flows such that for each iteration, path flows that do not go through current blockage links are increased by the available capacity of the most congested links. Cimellaro, Villa, and Bruneau [41] proposed a retrofit strategy to include emergency shutoff valves in the pipes for gas leakage prevention. Also, Sayed, Wang, and Bi [48] looked at the operational flexibility of the power plant and natural gas systems by modelling their physical and economic interactions to ensure the power system's resilience.

Recovery strategy

This strategy involves the steps taken after a disruption occurs. An example is seen in Almoghathawi, Barker, and Albert [50], where the research aim was to devise the most efficient way of tackling and restoring an interdependent infrastructure system to normalcy after partial destruction using an optimisation technique. Researchers in Bruneau et al. [38] introduced the resilience triangle (see Fig.) recovery strategy analytical tool for analytical assessment, while Jufri, Widiputra, and Jung [52] used it to describe the loss of functionality during the disruption. The measurement of resilience is a function of the plant functionality after a disruption and the time it takes to return to normalcy. The impact of the loss is measured by:

$$i = \int_{st}^{ft} [500 - J(t)] dt \tag{2.1}$$

where: $i =$ impact of the disruption, $st =$start time of the disruption, $ft =$end time when recovery is completed, $j(t) =$ the plant functionality at time t, and 500 is the fixed value that represents the total plant functionality in normal condition.

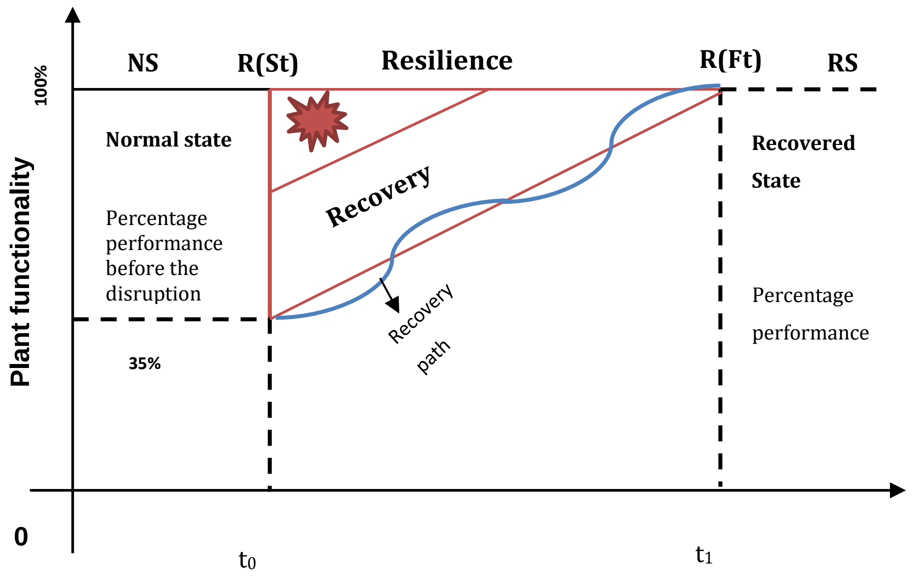


Figure 7: Resilience triangle associated with disruption

In Fig. 7, the plant functionality in time (t) is represented in the vertical and horizontal axes. The normal state (NS) is a 100 percent performance rate according to the specified functionality of the plant before the interruption at $\mathrm{R}(St)$. After the interruption, the recovery process takes place, and the recovery time is critical. It is expected that the plant functionality goes back to 100 percent using the concept of resilience. Recovery is fully achieved at $\mathrm{R}(Ft)$ when the recovery implementation state is at the resilience state (RS). This strategy is not ideal where a backup plan is not in place for the supply chain because it is time constrained.

Passive acceptance

The passive strategy means that no action is taken because the costs may outweigh the benefits. In Fig. 7, passive acceptance occurs when the plant's functionality drops to 35 percent from 100 percent, and no recovery action is carried out. The lack of recovery action is because the system operators and managers may decide to passively accept the disruption risk due to the possible cost implications and time constraints. It is usually a difficult decision to make but could be the best depending on the analysis carried out by the operators.

2.2 Mitigating disruptions through optimisation

When mitigation against disruptions is activated, it can tolerate flow disturbance through speedy recovery or provision of alternative means to satisfy demand. Schmitt and Singh [45] suggest that building flexibility through redundancy in a critical system is an option to make such a system more resilient. The process of redundancy can be referred to as a mitigation strategy. The mitigation approach involves specific technical and economically viable processes to operate through elimination, prevention, avoidance, and minimisation of possible adverse environmental impacts [30]. An IPCC report suggests robust evidence in the literature to support disruption decline as a strategy for long-term climate change adaptation [60]. In Fig. 8, the disruption effect on a supply chain's functionality is illustrated.

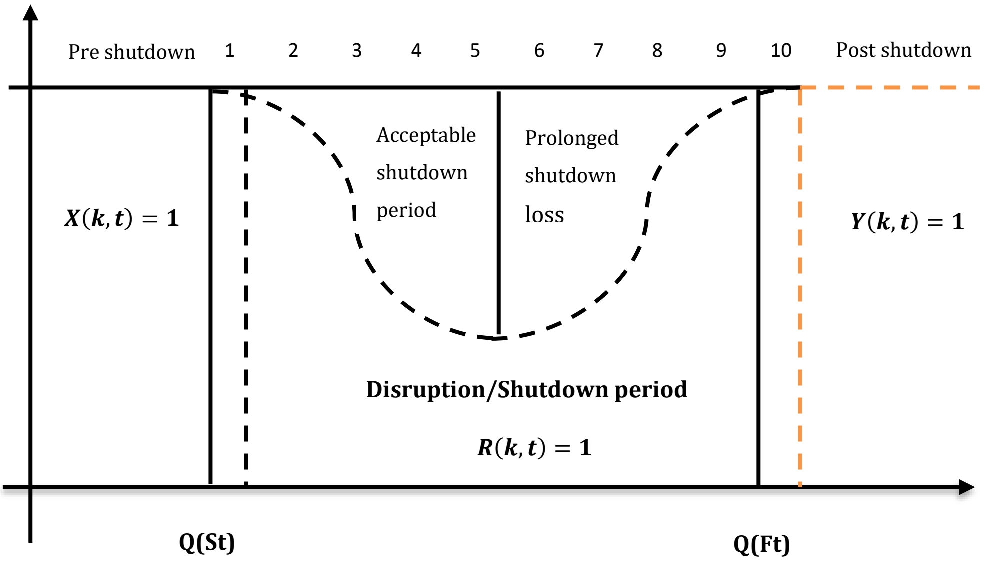


Figure 8: Disruption period (t) and loss from a plant shutdown

In the diagram in Fig. 8, $X(k,t)$ represents the period before the plant shutdown, $R(k,t)$ is the period of the plant shutdown, while $Y(k,t)$ is the point of recovery state of the plant. Also, Q(St) represents the beginning of the disruption, while Q(Ft) represents the point when recovery is completed. Fig. 8 demonstrates how interruptions can create allowable slack periods. Excesses from storage, if available, can be used to mitigate. The diagram also demonstrates possible loss when the shutdown exceeds the acceptable shutdown period.

2.3 Optimisation of supply chain

Optimisation involves reviewing the process to improve an existing system. It is a powerful and sophisticated tool to provide the structure needed to achieve the optimum solution to real-life problems. The search for an optimum (minimum or maximum) of a function defines the optimisation problem on a case-by-case basis. The security of supply from a fixed system is under pressure when there is disequilibrium between supply and demand at a given time horizon. For guaranteed investment decisions, appropriate frameworks to solve supply chain optimisation problems are required. As presented by different researchers, a few definitions of the supply chain are introduced to examine supply chain optimisation. A comprehensive definition of supply chain is a network of facilities that performs the procurement of materials, the transformation of these materials into intermediate and finished products, and the distribution of these finished products to consumers [61].

The supply chain is also described as a network of facilities and distribution mechanisms that perform material procurement functions, material transformation to finished products, and distribution of these products to customers [53]. However, after analysing several definitions of the supply chain, Hugo [62] concluded that supply chain management involves actions that individuals or managers do to stimulate the behaviour of the supply chain to achieve specific results. With the definitions above, it is reasonable to say that the movement of raw materials from suppliers to producers and the distribution of finished products from producers to final demand locations is a consumer satisfaction goal [16,53,61,63,64].

It is common knowledge that challenges are frequently encountered in supply chain nodes; therefore, managers tend to establish better performance standards to achieve efficiency in the entire supply chain line. An optimisation is usually introduced from time to time to meet the established standards [2,7]. Most of the optimisation models developed for supply chain networks have a common target of meeting demands on time, cost reduction, customer responsiveness, and supply efficiency through system flexibility. Developing an improved market-based supply chain system where all stages of the supply chain from supplier to the customer integrates adequately is essential to achieve targeted results. Supply chain development optimises production, transportation, and storage reserves of a secure system to respond swiftly to demand forecasts throughout a short to the medium-term period [55].

Recent research by Azadeh and Raoofi [66] explains that although supply chain optimisation goals traditionally focused on profit maximisation and customer satisfaction, there is a paradigm shift that introduces environmental and social concerns to supply chain optimisation in addition to economic goals [55,66]. Meaningful opportunities in this area include creating suitable procedures to assess the economic, environmental, policy, and social impacts of supply chains (refer to section 2.5). Unlike the economic and environmental dimensions, the social aspect is challenging to model and entirely ignored in most optimisation [67]. The reason for avoiding social optimisation is because it is difficult to quantify social elements. To this end, the social dimension is ignored in this supply planning and optimisation.

2.3.1 Classification of supply chain

Generally, supply chain classification helps to measure the performance of the supply chain and serves as a diagnostics control mechanism. Categorisation based on pre-operating and operating activities is on three broad categories. These include network design, simulation and policy formulation, and planning and scheduling. The network design, and simulation, and policy formulation are offline and pre-operating activities that establish the best option to design and manage supply chain network, whereas planning and scheduling category attempt to operate the existing network for optimal response to conditions that affect the supply chain or deals with the actual operation flow in the supply network [55].

For the network design, inevitable trade-offs such as cost variance based on location, production intricacy and efficiency, identifiable network pathways, and exchange rate variances are identified [55]. 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 also entails establishing the optimal procedure to design and manage supply chain networks, just like the design network type [55]. For the planning and scheduling problem type, decisions are adjusted continuously to optimise the network. Planning becomes crucial when the given constraints are established. According to Hamedi et al [16], the supply chain planning tool should be adopted so that demand forecast over a short to the medium-term horizon is achieved for a fixed network of production, transmission, and distribution resources.

There are three decision-level hierarchies in the supply chain planning based on time horizons for activities, as shown in Table 1. The decision levels are strategic, tactical, and operational. They can be differentiated in developing supply chain management depending on the time horizon [13,65]. The supply chain network design, simulation, policy formulation, and planning and scheduling are in tandem with these time horizons associated with the decision level hierarchies. These three decision levels are usually adopted for optimisation purposes.

The strategic decision level optimisation for supply chain considers time horizons of relatively long periods for up to fifty years [66]. The strategic level requires estimated and accumulated data and deals with the location of the facility and the design of network distribution. According to Mula et al [65], the strategic level covers the supply chain design, and its decisions are made based on the selection of production, storage, and distribution locations to minimise overall costs. The network design problem is a strategic decision level that requires a long-term time decision horizon. For a typical gas network optimisation problem, decisions such as new technology investment, the introduction of new transport and processing infrastructures are handled at the strategic level. Others include the development of gas fields and the maximisation of net present value [66].

The operational decision level for optimisation requires transactional and accurate data and considers real-time horizons on short but daily periods. For the operational decision level, replenishment and delivery operations are critical. The simulation and policy formulation problem type is at the operational decision level and is categorized based on replenishment and inventory allocation operations. Under the tactical decision level of the supply chain optimisation, production, inventory management, contract evaluation, transportation, and sales planning are handled. The tactical level decisions are usually made on a medium-term level from one week to two years [66].

The tactical level planning time horizon falls in between strategic and operational levels. However, the tactical decision level is ideal for distribution planning models as they identify aspects such as production planning and assigning both production and transport capacities. The use of tactical planning means that optimal capacity utilisation in flexible gas production fields can be found at this level. Most planning decision levels in the supply chain adopt the tactical decision level. If the tactical and operational decision levels are deployed, optimal use of existing production, transportation, and storage facilities is achieved to respond to high demand in the most efficient economical way for the supply planning and scheduling problem. This means that the planning problem is optimised over a short to medium time horizon. Table 1 summarises the different decision level hierarchies.

Table 1: Summary of decision level hierarchies

Decision Level	Time	Problem Type/Grouping	Activity	Data Requirement
Strategic	Long-term	Network design	Design of network distribution, location of the facility (production, storage, distribution)	Estimated and accumulated data
Tactical	Medium-term	Simulation and policy formulation	Distribution planning, production planning, inventory management, contract evaluation	Non-transactional data
Operational	Real-time, short-term	Planning and scheduling	Replenishment and delivery operations	Transactional and accurate data

2.4 The Natural Gas supply chain nodes

The natural gas supply chain primarily involves the physical infrastructure, business environment, telecommunications, and gas projects costing. However, it is broadly grouped into the production and transportation nodes linked and interconnected using the gas pipeline. Optimisation carried out on the production and transportation echelon in existing research works is further explained in section 2.5. The natural gas supply chain involves a batch of activities, also known as supply chain nodes. The activity levels and nodes are sometimes used interchangeably by researchers. Therefore, it is vital to state that the same has been applied to this work. The supply chain entails transporting natural gas from gas fields to the gathering hubs where gas from different suppliers or fields is mixed and then transferred to the processing plants and finally transported to the consumers. The pipeline and compressor are two vital components of the system required for efficient natural gas movement from source to consumer.

The general overview of the natural gas supply chain shows the upstream, midstream, and downstream activities, with each element interconnected. The schematic diagram in Fig. 9 displays the supply chain fixed physical entities of the natural gas represented by node components, while the current entities comprise the financial, information, and physical flows [16]. Based on the physical and current entities, existing research shows that the natural gas supply chain is extensive and complex [17] as it consists of several interconnected nodes (see Figs. 9 and 10). The gas network nodes can be analysed to increase supply, reduce loss, and minimise economic cost. However, the complexity of the system poses challenges for those managing the network because different operators and partners usually carry out the management of the individual components. Therefore, due to the complexity of the natural gas system, analysis is considered at different levels of the supply echelon [67]. The analysis includes detailed modelling of the pipeline, processing plant, compressor, storage facility, and city gate station. To capture the individual nodes appropriately, the subsections below explain each of these nodes in the supply chain and the constraints essential for assessing them.

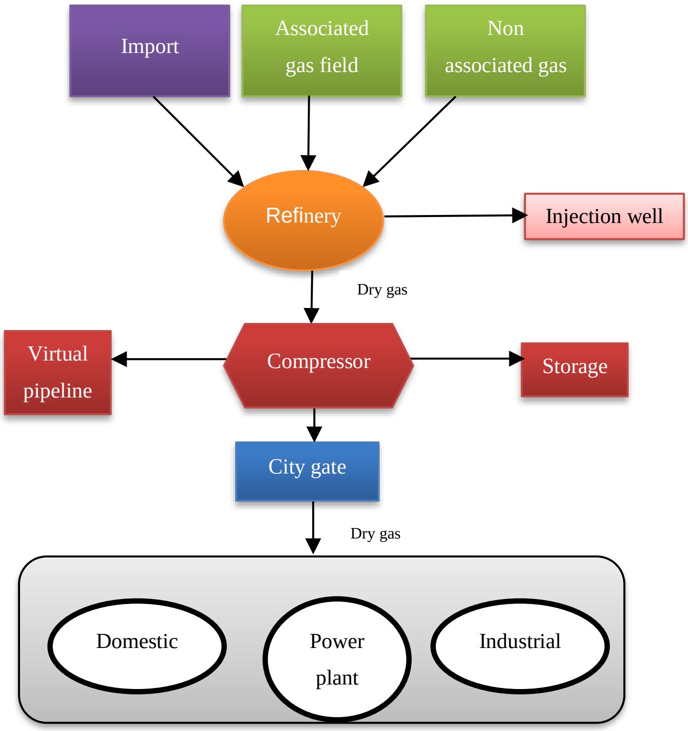


Figure 9: Schematic diagram of the natural gas network

Network components	Diagram	Nodes	Network components	Diagram	Nodes
Gas well	🟩	Production	Injection	▭	First-tier consumer
LNG import	🟪	Production	Virtual pipeline	🟥	Distribution
Gas processing plant	🟠	Processing	Natural gas company / City gate station	🟦	Distribution
Compressor	⬢	Transmission	Power Plant	⬭	Consumer
Pipeline	→	Transmission	Domestic/commercial	⬭	Consumer
Storage	🟥	Transmission	Industrial	⬭	Consumer

Figure 10: Physical entities of the natural gas network represented in nodes

2.4.1 Supplier node

The supplier node represents the gas fields, often owned by multiple parties with production rights to produce in commercial quantities. In the different gas fields, gas is extracted from reservoirs at elevated pressure and temperature (P, T_g) and consists of a mixture of hydrocarbon and non-hydrocarbon gaseous substances. Natural gas composition is primarily methane with a lower percentage of ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}), often accompanied by minor levels of impurities such as carbon dioxide (CO_2) and nitrogen (N_2) when combusted. Natural gas producing countries have different supply streams and harnessing these sources for reliable material availability is crucial.

Although the upstream and the downstream are the two primary sources of gas supply, there is the consideration for the mixture of the supply sources from multiple fields. If there are different sources available for material input, the aggregate supply from the suppliers must meet the total demand based on a contractual agreement between the sellers and the buyers. More importantly, is that the pressure at the delivery point should be within an acceptable pressure limit. In chapter three, the gas mixture from three different streams comprising the associated, non-associated, and import sources are used to determine the gas gravity (G) and to calculate the flow rate applied for the optimisation analysis. Generally, the natural gas production field is constrained by the following [24]:

Constraints:

- Production rates: This is determined by the volume of gas produced per unit of time.
- Contractual agreement: This refers to the commercial contract between the producers or gas company and the various consumers. In this instance, the three consumers referenced in this work are the power plants, commercial users, and households.
- Production capacity: In this constraint, gas suppliers' production capacity must be sufficient to meet demand.
- Reservoir management: This deals with projecting production to sustain and maximise recovery based on location.

2.4.2 Compressor node

The compressor is one of the vital nodes in the gas network system. It is used throughout the natural gas network to move gas from the upstream to the midstream and finally to the downstream at different pressures. In Menon [68], the compressor helps to exert pressure that has been lost due to friction in gas pipelines and to reduce volume by providing the necessary force to move the gas along the pipeline. Accordingly, the compressor receives gas at a pressure ranging from 200 to 600 pounds per square inch (psi) and compresses it back to about 1000 to 1400 psi [22]. It boosts the pressure in the pipeline by providing the required force to move gas in the pipeline. Typically, for every 100psi increase in pressure, there is a corresponding 7-8 degrees increase in temperature. There are majorly two types of compressors used in the gas network. The centrifugal compressor units are assembled in a sequence known as compressor station (see Fig. 11) and used with systems that demand high mass flow rates, low-pressure ratios, and an allowable compression ratio of 1.5. On the other hand, the reciprocating compressor achieves a high-pressure ratio [4]. A centrifugal dynamic movement characterises the centrifugal compressors, while positive displacements characterise the reciprocating compressors. The centrifugal compressor in a multiple of four in a compressor station is the available compressor unit for the case study under review.

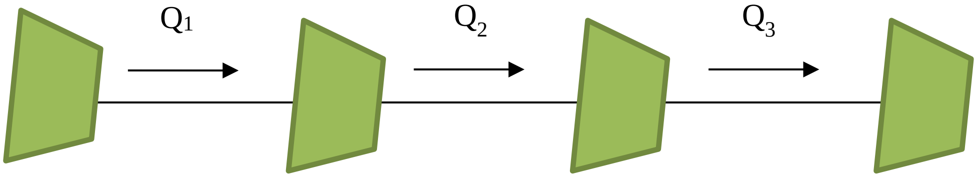


Figure 11: Multiple compressor stations [68]

A simple illustration shows that if the originating pressure at node ‘a’ is x(psi), and the flow rate is f(mmscfd), for an increase in the flow rate of f+1(mmscfd) to be achieved without modifying x(psi), the increased flow rate will cause a pressure drop at the delivery end of node ‘b’. If it is within an acceptable pressure limit, no penalty is incurred. The change in pressure is observed only in a dynamic state; however, the pressure is assumed to remain the same in the steady state. The following are some identified constraints [22].

Constraints:

- Mass flow rate: This is the mass of gas passing through the compressor per time.
- Shutdown (maintenance & emergency): This refers to the number of times the compressors have been shutdown caused by a disruption in the planning horizon.
- Pressure ratio: This refers to the gas pressure in the inlet/outlet of the compressor.
- Gas temperature: This refers to the gas temperature in the pipeline.

2.4.3 Storage node

Gas storage is used primarily to meet demand and load variations. Injected gas into storage during periods of low demand and withdrawn from storage during periods of peak demand is determined by the deliverability in the storage facility. If the transported gas is not immediately needed, it can be stored in a storage facility. Usually, the capacity of the dedicated storage is determined by demand fluctuation. Along with gas reservoirs or gas holders, the pipeline itself can be used for gas storage, known as line packing. Often, this line packing is for temporary storage and does not hold gas for an extended period. Where storage relies on online packing, there is a limit to which the pipeline can be utilised for temporary storage. There are three widely known underground storage tanks known as the depleted gas reservoir, the aquifer reservoir, and the salt caverns. The storage system can be installed at different points in the supply chain between the transmission and distribution system. Strategically, underground gas storage provides the security of supply if there are disruptions to production and transmission. This could be due to commercial reasons, such as sales gas price negotiation, political reasons, or an outage. It is a means to balance seasonal variations in consumption. Some storage constraints are listed below [22,69].

Constraints:

- Storage capacity: This refers to the temporary storage capacity in the pipeline.
- Deliverability/withdrawal rate: This is the amount of gas that can be delivered (withdrawn) at time (t) from the temporary storage.
- Gas demand uncertainty: This storage quantity is affected by demand fluctuation.

- Injection rate: This is the amount of gas injected into the temporary storage at time (t) usually expressed in mmscfd.

2.4.4 Processing plant node

A refining plant processes the gas to meet the available pipeline transportation standards and specifications. The natural gas is almost entirely methane when it is dry and when all other associated hydrocarbons are removed [30]. This process entails collecting unprocessed gas from gas fields and gas gathering facilities into a refining facility for treatment and processing to produce pipeline-quality dry gas in the processing plant. Here, unprocessed gas is dehydrated to acceptable standards, and any element of undesirable compounds of carbons, sulphur, and mercury are removed before onward transmission. 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 as condensates, and under normal atmospheric pressure, they become sold as natural gas liquid with economic value. The constraints [15] include:

Constraints:

- Gas-feed composition: The feed composition determines the actual processes used.
- Processing time: This is the total amount of time it takes to treat the natural gas.
- Mass flow rate: This is the amount of gas that passes the refinery node per time.

2.4.5 Pipeline node

The physical flow of raw materials through the pipeline is the most palpable aspect of supply chain activity in the gas sector. The pipeline is the long-distance transportation for natural gas that connects intra and inter-states across various regions. Therefore, pipelines are the primary means of transportation from gas suppliers to consumers. However, developing economies with a vast natural gas deposit like Nigeria faces a significant challenge with limited infrastructural development as shown in Fig. 12. The Africa region is challenged with underdeveloped pipeline infrastructure, unlike Europe, for instance, where the gas network consists of interconnected pipelines (see Fig. 13) of over 100,000 km in length [70].

Figure 12: Gas pipeline network in Nigeria [71]

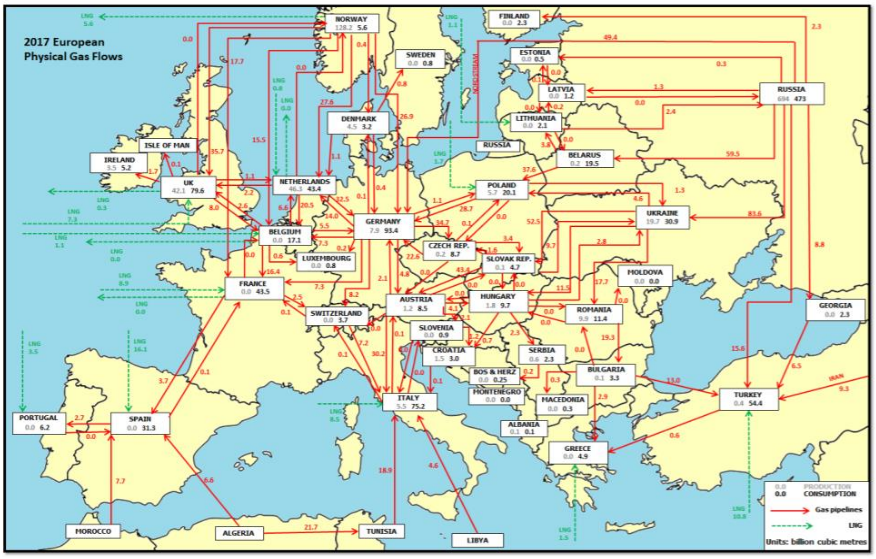


Figure 13: European gas pipeline system [8]

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. The strength of the steel pipe is welded into long sections that allow gas to be carried under higher pressure and large quantities over long miles. There are three types of pipes in the gas network system differentiated by their length and diameter, varying depending on their specific usage. They are explained further below.

Gathering pipes are used for collecting raw products from the gas fields, and they 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 bigger than the gathering and distribution pipes. They transport large quantities of natural gas across thousands of miles from the processing facility to distribution pipelines 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 in which locations are easily accessible are already tapped. The distribution pipes operate at low and medium pressure and consist of a network of small-diameter pipes. There are usually no compressors, nozzles, or valves along the distribution pipes.

The gas quantity transported at time (t) is determined by the diameter (d) of the pipeline and the pressure (p) exerted by the compressor (k) along the pipeline route. Moreover, the length and diameter of a pipe influence the gas dynamics. At the endpoints, the pressure difference depends on the pipeline length and size for a fixed amount of flow [70]. As shown below in Fig. 14, is the gas pipeline displayed as a linear function of inlet pressure and outlet pressure, which can only feed consumers along its route and $P_1 = P_2$. In the transmission pipeline, gas is conveyed in a forward flow from suppliers through the transmission and distribution echelons to the consumers. Summarised below are the identified relevant constraints for the pipeline node [22].

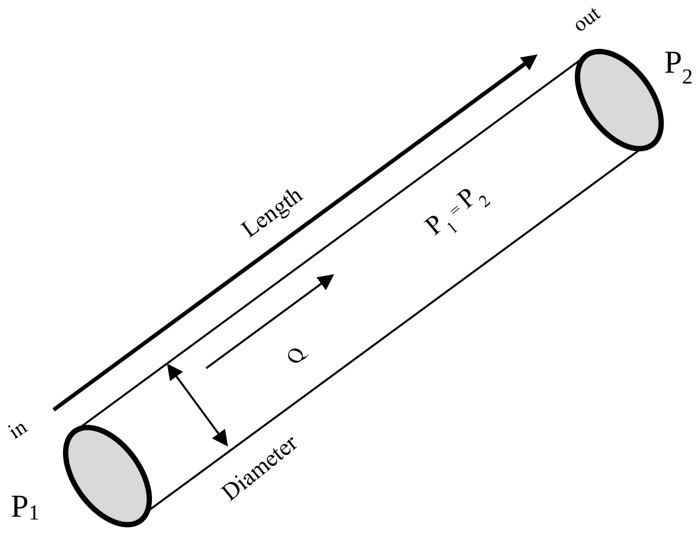


Figure 14: A linear flow of gas in a pipeline

Constraints:

- Pipe capacity: This is the required amount of gas that the pipeline can contain. It is a combination of the pipeline diameter and length.
- Pipe length: This is the distance between two or more compressor stations.
- Pipeline pressure and temperature: This is the required pressure and temperature range determined by specific parameters within which the gas in the pipeline is expected to flow.
- Gas flow rate: This is the amount of gas that passes the pipeline node per time t.
- Gas quality: This refers to how close the gas is entirely methane and within the pipeline required standard. It also determines the efficiency of the gas flow.
- Compression ratio: This refers to the compression ratio of the pipeline compressor, which allows for continuous flow even after the upstream valve is shut.
- Open and close rate of the valve: This constraint allows for the free flow of gas and flows restriction in the natural gas supply chain's disrupted section.

2.4.6 City gate station node

The natural gas company is usually in charge of operating the city gate station (CGS). The CGS is a measurement, pressure control, and reducing package that contains a metering system. The CGS is a point at which a local gas utility receives gas from a transmission system. It supplies gas to household and industrial customers at the required consumption pressure of less than 300 psi from over several hundred psi. The CGS is found in the distribution echelon of the supply chain. Identified constraints are summarised below [72].

Constraints:

- Required consumption pressure: This is the required pressure at the consumer node.
- Temperature: This constraint ensures the temperature is not reduced to the level where hydrates are formed, which causes blockage.
- Pipe diameter and length: This refers to the delivery pipeline size. The pipeline size must be sufficient for the required pressure.

2.4.7 Consumer node

Generally, there are several gas end receivers found in the consumer node. The gas-fired plant, household, commercial, and industrial are some of the end-user consumers of natural gas. First-tier consumers may include re-injection wells. Summarised below are the identified relevant constraints [72].

Constraints:

- Power grid capacity: The capacity of the power grid can affect the supply flow from the compressor or city gate.
- Demand: The fluctuation in demand can be due to weather conditions, change in pricing, or purchasing power change.
- Distribution pipeline pressure: The gas pressure from the transmission pipeline into the distribution must be within the required minimum and maximum pressure.

2.5 Natural Gas supply chain optimisation

Optimising the production, transmission, and distribution flow for best results guarantees natural gas availability regardless of weather conditions, demand fluctuation during seasonal changes, price variation, and periodic plant maintenance that are likely to cause disrupted flow in the supply chain. The optimisation entails achieving overall supply efficiency in satisfying demand growth while considering external factors as additional possible constraints. These gas supply chain levels are interconnected and should be modelled in an integrated manner. Available literature have investigated the supply chain of natural gas through optimisation [16,53,54,72–74]. The common objective is to enhance efficiency and overall economic cost reduction in the supply chain.

Few studies have attempted to optimise the entire supply chain of natural gas [16,75]; other studies have optimised the supply chain at different levels of the echelon [76,77]. Optimisation from researchers and industry experts often has been carried out along the production, transmission, distribution, and storage echelons over a short to the medium-term period [53,54]. Although transmission and distribution echelons are usually separated, Hamedi et al. [16] suggest that both the processes, when merged, would form a single integrated distribution entity known as transportation. Depending on the researcher, the groupings of the entire gas supply chain varies between three to six echelons.

The production entails the refining of gas collected from gas fields or import, while the transmission and distribution determine how the products are retrieved directly from the refineries and then transported to consumers for various forms of consumption. Along the transmission and distribution networks are the gas pipelines and compressor stations. Specifically, the transmission involves gathering and intra/interstate pipeline systems to transfer gas from wellheads to the local gas company at high pressure. In contrast, the pipeline system delivers gas at lower pressure to the power plant or intermediate consumers for distribution. The distribution and transmission elements are a crucial part of the gas supply chain, and they constitute 30 percent of the natural gas cost price [16]. Although there are gas networks with dedicated storage, sometimes the gas is stored in the pipeline due to its compressibility for the short-term known as line packing.

For the modelling of production, transmission, and distribution levels of the gas supply chain, [72] synchronised these different levels of the supply chain as a portfolio of activities by providing insights into planning complexities. The modelling was based on the steady state mathematical formulation of transportation in the gas network. With the introduction of multi-material input flows, estimating the terminal value in the storages within a time horizon, and the stochasticity in demands, contract price, and spot prices, the researcher developed a stochastic programming formulation for a portfolio optimisation model which represents uncertainty in the model. Researchers also modelled these three levels of the gas supply chain where lack of dedicated storage, causing interruptible services and demand fluctuation, was a critical factor considered to provide a solution to absorb short term variations [73].

An optimisation model was developed to examine optimum solutions for a given function; this means that when a supply chain is optimised, it results in optimal distribution and allocation of scarce resources through the smooth flow of products at the least cost possible [78]. For natural gas, the optimisation goal, which hitherto focused on profit maximisation through cost minimisation and customer satisfaction, introduces environmental and social concerns currently to its economic goals. For instance, [75] introduced environmental cost in addition to economic cost reduction in their research. In the optimisation of the supply chain, planning becomes crucial when the given constraints are established. Identifying the fields where the gas is collected, locating the gas gathering facility and the compressor stations, laying the pipelines to the closest and functioning power plant facilities, and locating where virtual pipelines will be more appropriate, are part of the planning for a typical gas energy supply chain. For the actual operation, the configuration of the supply chain is fixed when planning policies are defined [79]. According to Hamedi et al. [16], there is a need for the supply chain-planning tool to be adopted so that demand forecast over a short to medium-term horizon can be met for a fixed network of production, transmission, and distribution resources.

2.5.1 Production optimisation

Not much work has been done on the production optimisation of natural gas compared to the transportation optimisation. According to Xiang, Tomasgard, and Barton [80], mathematical programming has been generally used to plan natural gas production infrastructure development. The production entails the activities in the production well and the processing facility. For Xiang, Tomasgard, and Barton [80] stochastic programming model was proposed over deterministic optimisation models to obtain an optimal solution using two-stage stochastic programming models to facilitate natural gas production infrastructure growth under uncertainty. The first is the stochastic pooling model that uses a generalized pooling model to track the qualities of gas streams throughout the production network. The second considers pressure to improve the stochastic pooling model.

2.5.2 Transportation optimisation

As already established, transmission and distribution could be used as a single integrated transportation entity. A considerable amount of work has been carried out on gas transportation network optimisation ranging from pipeline cost minimisation, capacity expansion, and energy consumption minimisation [73] but minimal emphasises on the resilience. Available studies on the transmission and distribution of natural gas focus on the gas pipeline and compressor station. For instance, Kabirian and Hemmati [77] developed a strategic planning model for natural gas networks such that the optimisation of the nonlinear model addresses the short-run development plan where the location of compressor stations, pipeline routes, and sources of natural gas was considered to reduce transmission network cost while meeting increasing energy demand. The model also developed a heuristic random search algorithm to provide optimal development plans in a long-run planning horizon.

In Hamedi et al [16], a transportation planning model for the natural gas supply chain was studied using a mathematical stochastic modelling approach in a tactical decision level to minimise related costs attributed to transportation and to utilise operational capacity for the reduction in product shortages. An optimisation model for integrated distribution planning was introduced at every stage of a six-level supply chain. Although demand uncertainty was based on weather conditions, the researchers assumed the average consumption of the previous periods for the demand of all consumption groups. Hellemo et al. [81] used a deterministic model in a strategic decision level where the natural gas network design is considered an investment problem. Existing infrastructure was considered for potential expansion from a system perspective. The existing infrastructure model was extended by adding pressure flow relationships in a deterministic mixed-integer linear program.

In a recent study on natural gas transportation optimisation problem Ríos-Mercado and Borraz-Sánchez [22] analysed a steady state model based on time by adopting a stochastic approach which focused on the pipeline and other physical entities in the pipeline like the valves and the compressor. The researchers investigated line packing issues by using pipelines for short-term storage. The essence was to fill the gap associated with seasonal demand. The researchers tried to solve the problem from an operational perspective rather than a managerial perspective. A simulation model for the natural gas pipeline transmission network was considered in Woldeyohannes and Majid [82]. The model incorporates parameters known to be critical to the performance of the compressors, such as speed, flow rate, suction pressure, discharge pressures, and suction temperature, into the equation. The focus of the work was to increase capacity flow in the transmission network and reduce power consumption, which has a direct impact on the performance of the system. As an extension of Woldeyohannes and Majid [82], an optimal solution of steady state transportation problems on two levels was addressed in Sedliak and Zacik [83]. The first level is the optimisation of the compressor station, which is the local level, and the second level is the optimisation of the pipeline network, which is the global level. The solution was based on a steady state simulation and evolution strategy algorithm bringing about an integration of deterministic and stochastic elements to form the modified algorithm of evolution strategies by assigning the value of fitness function and verifying feasibility. Also, to improve the active control for gas transmission systems Sukharev and Kosova [84] considered the problem associated with technical parameter identification in an unsteady state using a nonlinear model.

2.6 Sustainability in supply chain optimisation

A broad array of different perspectives have been discussed by researchers since the inception of sustainability depending on the application by the users. To appreciate sustainability as a long-term goal, the understanding of sustainable development which is the pathway to achieve sustainability is important. An acceptable definition of sustainable development as proposed in the Brundtland report [85], is “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” The multiple objectives of economic, resource, social, and environmental goals in a supply chain is a comprehensive strategy for sustainability [86,87]. In environmental sustainability, all types of resources are expected to be utilised efficiently to reduce the negative impact of losses on the environment. A truly sustainable energy future ensures loss minimisation in the supply chain and a lesser carbon footprint [88]. Türkay et al. [89] argued that supply chain efficiency optimisation can be achieved without jeopardizing the environment. For instance, to guarantee the future of the network in a gas supply chain, the minimisation of environmental impact, associated cost, and sustainability is fundamental [90]. Some researchers have introduced environmental effects to natural gas optimisation such that economic cost and cost associated with greenhouse emissions were minimised [75]. The study considered the ergonomics that involved the human element, with plant and environment interface. Generally, the concept of natural gas supply chain sustainability optimisation is one reason to mitigate against frequent and prolonged disruption to minimise recorded loss and emission to the environment.

Economic sustainability is of prime importance for most supply chains, where the goal of the optimisation is to minimise costs or maximise profit [19]. Although unpopular yet relevant, resource sustainability deals with fully utilising infrastructure for optimal results and least impact the environment, while social sustainability deals with considering consumers first in production planning. Generic supply chains design and planning, sustainable supply chains, and emergent supply chains are three types of supply chains. This work is limited to generic supply chain planning and a sustainable supply chain. This allows for incorporating sustainability concerns into supply chain planning and optimisation.

2.7 Optimisation modelling techniques for Natural Gas supply chain

An optimisation is a powerful and sophisticated framework for addressing real-life problems in engineering. It is used for minimisation or maximisation of a function subject to its constraints [91]. Though optimisation techniques have been applied to many aspects of the supply chain, it is required for the entire supply chain line to achieve cost and environmental efficiency. The focus for organisations is to meet the ever-increasing sophisticated consumer demand, hence optimising the supply chain becomes relevant [16]. Although some literature works have suggested the best possible ways to improve the efficiency of the gas supply chain by designing various mathematical models or by analysing problems in certain areas within the supply chain, it is relevant to consider all echelons in the supply chain for optimisation. Mathematical programming or simulation models and their application generally depend on what the researcher tends to address [53]. The challenge of selecting an effective optimisation technique for real-life supply chain optimisation models in a complex problem requires careful analysis of the supply chain, especially in production and transportation planning problems. According to Fahimnia et al. [92], optimisation solution techniques can be categorised into four groups. In this work, further explanation of the mathematical modelling and simulation are presented below.

2.7.1 Mathematical modelling technique

Mathematical techniques involve mathematical expressions by formulating equations with objective function and constraints that are usually difficult to formulate. Supply chain models that adopt mathematical programming optimise high-level decisions that involve unspecified configurations, taking a total assessment of the dynamics and detail of the operations such as the design network, medium-term production, and supply planning [53]. In the real world, the use of a mathematical model is limited because it ignores the realism of the desired events [93,94]. Notwithstanding, quite a few researchers have applied mathematical modelling tools to study and improve supply chains [16,94–96]. Mathematical optimisation problems are categorised into the following techniques.

Linear programming modelling approach:

Linear programming (LP) studies the case in which the objective function is linear, and the set is specified using only linear equalities and inequalities. It does not include nonlinear binary or integers variables.

Objective function $f\ (x_1, x_2, \cdots x_n)$ (2.1)

The objective function for linear programming minimises or maximise the objective function. The objective function of the linear programming model is subject to one or more constraints.

Constraints:

$b_1x_1 + \cdots + b_nx_n = y$ (equality constraint) (2.2)

$b_1x_1 + \cdots + b_nx_n < y$ (inequality constraint) (2.3)

$b_1x_1 + \cdots + b_nx_n > y$ (inequality constraint) (2.4)

$b_1x_1 + \cdots + a_nx_n \leq y$ (inequality constraint) (2.5)

$b_1x_1 + \cdots + b_nx_n \geq y$ (inequality constraint) (2.6)

where 1…. n represents the sets, $b_1 + \cdots + b_n$ represents the parameters, $x_1 + \cdots + x_n$ represents the variables, while y represents upper and lower bounds. The formulated single linear function objective criterion is limited [97]; however, the limitation can be overcome by introducing multiple criteria objective and multiple constraints [98].

The versatility and applicability of linear programming to large and complex problems make it a more acceptable type of modelling tool [99]. In a study carried out by Mula et al [100], the researcher explains that the linear programming approach presented in Kanyalkar and Adil; Chen and Wang; Jung, Jeong, and Lee; Martin, Dent, and Eckhart; Oh and Karimi; Ryu, Dua, and Pistikopoulos [96,101–105] was used in integrated supply, planning production, inventory operations, and distribution. One thing that characterises the objective function is addressing a multi-period, multi-product [96,104], and multi-objective [106–108] across different industries. In Vasconcelos et al [109], the researchers obtained maximum network flow using linear mathematical programming in a modelled gas pipeline flow. The importance of linear programming is that it is used to study system behaviours; thus, it describes the interrelations of system components [110].

Mixed integer programming modelling approach:

The mixed integer programming (MIP) or MILP is a more widely used modelling approach based on the body of literature reviewed in Mula et al. [65] for production planning and transportation problems. With a MIP, integer values are introduced as one or some of the variables. Accordingly, the decision-maker is faced with linear constraints and objective function with some integer or binary variables in a MIP problem. The MIP is more challenging to solve and technically tricky than linear or convex but can solve a yes or no decision problem. The literature that used the mixed integer linear model applied it across the three decision levels. Different strategies of applying the model, such as decentralised two-stage model [111], heuristic relation techniques [111], differing time scales [112,113], multi-product and multi-period [114,115], and genetic algorithm technique [116] were applied to differentiate between the researcher's works distinctively.

An example of a MILP model for a gas supply optimisation under demand uncertainty is provided in Contesse, Ferrer, and Muturana [73]; the researchers developed a multi-period mixed integer programming model in purchasing and transportation contracts optimisation where the gas is not extracted locally but imported. The gas supply chain was at three levels comprising producers, transmission, and distribution. In the absence of storage facilities, the model considered transportation complexities to help optimise daily transportation decisions. However, a more recent work in Incekara and Ogulata [117] on mixed integer linear programming added environmental concerns to reduce GHG emission. Generally, for MIP, an additional condition is added such that at least one of the variables can take on integer values only. Mathematically, the MIP problem is therefore represented as:

Min/Max:

Objective function $$F = CS \tag{2.7}$$

Subject to:

equalities and inequalities constraints $WS \le r, S \ge 0$ (2.8)

Then:

$$S = (s_1, s_2 \dots, s_n)'$$
$$C = (c_1, c_2 \dots, c_n)$$
$$r = (r_{1,} r_2 \dots, r_n)'$$
$$W = \begin{bmatrix} w_{11} & .. & w_{1n} \\ \vdots & & \vdots \\ w_{m1} & .. & w_{mn} \end{bmatrix}$$

where $F = CS$ is the linear function to be optimised, S represents variable to be determined, C represents known coefficients, values to the right, $(s_1, s_2 \dots, s_n)'$, $(c_1, c_2 \dots, c_n)$, $(r_{1,} r_2 \dots, r_n)'$ are the resource limitations, $w_{11} .. w_{1n}$ and $w_{m1} .. w_{mn}$ are the equalities and inequalities also called constraints.

Nonlinear programming modelling approach:

Unlike LP, nonlinear programming (NLP) studies the general case in which the objective function or the constraints or both contain nonlinear parts [97,118]. A reference work is found in Kabirian and Hemmati [77] where a strategic planning model for natural gas networks was developed. The optimisation of the nonlinear model addressed the short-run development plan considering the location of compressor stations, pipeline routes, and sources from which natural gas is procured to reduce transmission network cost. In addition to the planning model, the researchers also developed a heuristic random search algorithm to provide optimal development plans in a long-run planning horizon. Their research focused on the transmission of the gas supply chain of an existing natural gas network to meet increasing energy demand.

Mixed integer nonlinear programming modelling approach:

The mixed integer nonlinear programming (MINLP) combines integer variables and nonlinear functions used to solve challenging optimisation problems. For instance, an optimisation model developed for integrated distribution planning adopted a MINLP for distribution planning at every stage of six levels of the natural gas supply chain network [16]. When merged, the researchers assume that both the transmission and distribution processes would form a single distribution entity. The focus was to reduce related costs to the integrated distribution systems such that consumers can only experience minimal shortages. MINLP can be analysed both in deterministic and stochastic environments. Although demand and prices are generally stochastic, Lababidi et al. [119] proposed a deterministic mixed integer nonlinear programming model.

Fuzzy and deterministic programming modelling approach:

Fuzzy represents the uncertainty or vagueness in a problem, and it is a method for modelling uncertainty. Uncertainty can arise instinctively in different applications; therefore, modellers adopt different solution approaches for modelling. Fuzzy optimisation algorithms use these measurements of uncertainty to generate solutions that optimise the expected performance of the model. For instance, if the disruption of the plant is uncertain, the need for a fuzzy logic optimisation formulation model will be introduced, which include an acceptable error margin because of the vagueness of the model. The objective for the optimisation formulation for the plant shutdown will be represented in the equation as:

$$\text{Minimise} = \frac{1}{S} \quad \sum_{S=1}^{S} \; f'(f_s) \tag{2.9}$$

This can be expanded as:

$$\text{Minimise} = \frac{1}{Z_2} \quad \sum_{Z_2=1}^{Z_2} \; f'(f\delta_s) \tag{2.10}$$

$f' =$ fuzzy scaling factor objective (constant parameters)

$f' = Oi;\ Oi =$ experimental value of the objective function number i

Objective Oi has a satisfaction interval of 2* Ei wide; $Ei =$ acceptable error margin.

$s =$ min/max fuzzy scale factors (parameter)

$f =$ min/max value of the objective function number i

$\delta =$ coefficient for fuzzy scale factor

While researchers like Selim, Araz, and Ozkarahan; Sakawa, Nishizaki, and Uemura [107,120] proposed fuzzy objectives and parameters in their work, Azadeh, Raoofi, and Zarrin [75] researched the evaluation and optimisation of the natural gas supply chain using a multi-objective, multi-period fuzzy linear programming model with a focus on economic and environmental objectives. For multi-product and multi-period production and distribution planning, Aliev et al. [121] used an integrated fuzzy linear programming model. A fuzzy mixed integer programming model was developed by Liang and Cheng [122] using fuzzy multi-objective linear programming in a multi-period and multi-product environment. To combine production, delivery, and demand uncertainty, Sabri and Beamon [123] used a multi-objective analysis as a performance measure for the supply chain model that facilitates simultaneous strategic and operational decision planning levels.

In contrast, Hamedi et al. [16] considered the uncertainty associated with demand from household consumers due to weather variability; however, the uncertainty can be adjusted such that consumption is estimated from previous trends. Energy sources associated with uncertainties like weather conditions, government policies, demand, product availability, and underdeveloped technology make it more difficult for near accurate modelling. Hence Lee [124] emphasises the challenges associated with modelling with this type of scenario and proposes a synchronized and closely integrated system of multiple solutions approaches for all energy sources to meet the increasing energy demand.

The deterministic model indicates certainty in data parameters devoid of randomness. In deterministic modelling, outcomes are known because inputs are fixed, and all parameters are known or expected. For deterministic programming, Ishii, Takahashi, and Muramatsu [125] developed a deterministic model that determines economic levels for the base stock and lead times for production and transportation in integrated production, inventory, and distribution systems. The purpose of the base stock and lead time was to prevent stock out of products when production and transportation are not operational for a period. A researcher presented a system perspective model incorporating a deterministic mixed-integer linear program for a strategic natural gas infrastructure expansion [81]. The deterministic model has an advantage when the available data can result in a fixed output determined by the parameters and initial conditions such that they have a cause-effect relationship.

However, Mirzapour Al-e-hashem, Malekly, and Aryanezhad [126] argues that decisions hinged on deterministic models face a risk when demand is not satisfied with the right products as specific parameters like demand, price, and manufacturing capacity may be unknown. As such, the need for a robust model arises to accommodate uncertainties to avoid performance inefficiency caused by delay. To account for uncertainties in real-world problems, Mirzapour Al-e-hashem, Malekly, and Aryanezhad [126] listed some programming techniques employed to help deal with such problems: stochastic programming, fuzzy set theory, robust optimisation, and stochastic dynamic programming. One area where the stochastic model is needed is when influences from the environment, such as weather conditions [127] and social factors, are considered. On the contrary, Wets [128] argues that though some levels of uncertainty exist about system parameters, not much is lost, usually by assuming that the value of the parameters is known, especially where such parameters are not central in the analysis of the system. However, when the parameter plays a significant role in analysing the system, such uncertainty cannot be ignored.

Hybrid programming modelling approach:

The hybrid approach is a combination of alternatives, such as integrating mathematical programming and simulation models, as seen in Lee and Kim [13]. However, for production, storage, and distribution planning, a hybrid model was developed with the specificity of using both a mixed integer linear programming and discrete simulation model [129]. Simulation models are optimisation techniques used to analyse the exhaustive dynamic process of a fixed structure under operational uncertainty. This can be applied to evaluate anticipated performance processes for the fixed design to a high level of precision. The simulation model predicts the outcome of a single specified set of design or policy variables. Unlike mathematical optimisation models, simulations do not narrow the search for optimal policies or design for a problem. Optimisation models provide a means of reducing the number of alternatives that need to be simulated in detail. Due to the high complexity that affects oil and gas supply chains and the challenges in developing an accurate mathematical model, Kbah, Erdil, and Aqlan [130] suggests the application of simulation methods as an appropriate technique to provide a detailed and dynamic view of the supply chain. Arguably, simulation is used in evaluating expected performance measures of a fixed configuration to a high level of accuracy [53].

The modelling approaches described above can be summarised in Table 2 below.

Table 2: Classification of optimisation techniques

S/N	Mathematical Modelling Method	Advantages	Disadvantages
1	Linear programming-based modelling approach (LP)	Linearity of objective function *f*	Difficulty in defining specific objective function
2	Mixed Integer Linear Programming (MILP)	Linear solvers, flexibility of model, and global optimality	Lack of nonlinearity effect, risk of high dimensionality of problem
3	Nonlinear Programming Based Modelling (NLP)	Algorithm replaces a given problem by linear approximation	The objective function *f* and constraints are non-linear
4	Mixed Integer Nonlinear Programming	Can solve large problems and used MILP techniques	The objective function and /or constraints are nonlinear with continuous and discrete variables
5	Fuzzy, Stochastic and Deterministic Mathematical Programming	The fuzzy and stochastic elements deal with problems of uncertainty, while the deterministic element deals with known parameters	Search for an optimal solution involves randomness. Deterministic approach is not realistic.
6	Hybrid Programming	Effective in solving larger optimisation problems.	More cumbersome to program

2.8 Conclusion

In chapter two, available and relevant scientific research work on the supply chain resilience is reviewed to understand the implementation of different strategies to enhance the natural gas supply chain resilience. In particular, the disruption and shutdown period is highlighted, and the various resilience strategies explained. Mitigation has been identified as the best strategy for this research because of anticipatory actions taken to lessen the impact the risks. In this chapter, it has been established that optimisation is necessary to provide the structure needed to achieve the optimum solution for the supply chain and optimisation is a necessary tool in mitigation planning. This chapter also shows that mathematical modelling and optimisation are relevant tools for complex supply chain problems.

This chapter provides a resilient supply chain in a deterministic environment identified as less complicated to achieve. If a resilient supply chain is achieved in a deterministic environment, it can be argued that the supply chain optimised is more realistic, in contrast to a non-deterministic environment where stochastic programming is adopted even though uncertainty is a necessary occurrence. However, logical consideration of uncertainty can help estimate future expectations, calculate likely returns, and estimate associated risks. Paul, Sarker, and Essam; Midthun et al. [56,66] postulates a paradigm shift that introduces environmental and social concerns to supply chain optimisation in addition to economic goals. A critical analysis shows that existing studied research focus majorly on cost or profit optimisation, and energy consumption minimisation of the natural gas transmission network. In addition, others have optimised from the system perspective aimed at achieving consumption minimisation. However, no existing work has optimised the throughput using a system-based approach by identifying the most appropriate mitigation strategy for a prolonged disrupted interconnected gas supply chain system. Therefore, this research has become relevant to consider the environmental factor as an essential sustainability element.

Based on the arguments from the extensive literature review, it is feasible to infer that very minimal research has considered developing a comprehensive framework to deal with unplanned disruption to the gas supply chain. Moreover, most of the studied literature optimises for cost, profit, and energy consumption of the transmission networks when compared to system-based natural gas supply chain resilience. Therefore, it is safe to say that detailed research is needed for a novel resilience-driven optimisation model to maximise the throughput and minimise the associated CO_2 emissions. The research gap identified has led to the research questions listed in chapter one. Although most deterministic models are known for optimising either supply chain cost or profitability, the identified research gap is to build upon the works of the literature reviewed by adopting a system-based approach where performance measures like resilience and loss savings are introduced in the modelling.

This chapter also presents studies that show how the complexity of a supply chain impacts its resilience. This chapter identifies the mitigation strategy as the most appropriate approach for this research based on exogenous disruption. In this research review, existing literature indicates that developing a resilient supply chain system in the wake of rising global demand is a top priority for supply chain optimisation. In this chapter, it has been established that accelerating energy consumption, coupled with uncertainties, and disruptions, is a significant challenge in the 21st century. Therefore, it is essential to provide a functional and responsive supply chain to deal with the movement of products from sellers to consumers. Most modelling techniques have supported supply chain optimisation using different modelling tools though no generally approved optimisation method exists.

Factors of disruption will impinge on the continuous supply of products to consumers in the short, mid, and long term. Project managers and engineers continue to optimise for cost reduction, system flexibility, reliability, and efficiency to reduce the impact of such disruptions and the optimisation guarantees resilience in the supply chain. To show the novel strategy for studying energy supply chains that are susceptible to disruptions under different states, a typical natural gas supply chain has been selected as a case study. The infrastructure composition and the overview of the NG proposed workflow are described in chapter three of this work. The novelty of this research lies in the study of the mitigation planning problem (MPP) and the impact of redundancy on the NG supply chain using a MILP model that integrates resilience and CO2-eq loss. To the best of the researcher's knowledge, no detailed systematic approach currently exists to deal with shutdowns in a deterministic environment.

Chapter 3

Case Study: Modelling of the Gas Supply Chain

Chapter three seeks to establish the case study and highlight the problem associated with the case study. Upon identifying the associated problems, a workflow is proposed, and to determine the capacity of the proposed workflow, the gas gravity, pressure, and compressibility factor are introduced as basic functions. Estimating the required flow rate of the proposed workflow is done by calculating the flow rate required for the relief pipeline, the pressure, and the compressibility factor. This chapter is introduced to show how the gas compressibility is affected by gas gravity and the average pressure. The impact of the compressibility factor in determining the gas flow rate is also established. Fig. 15 is a representation that illustrates the steps of the chapter analysis.

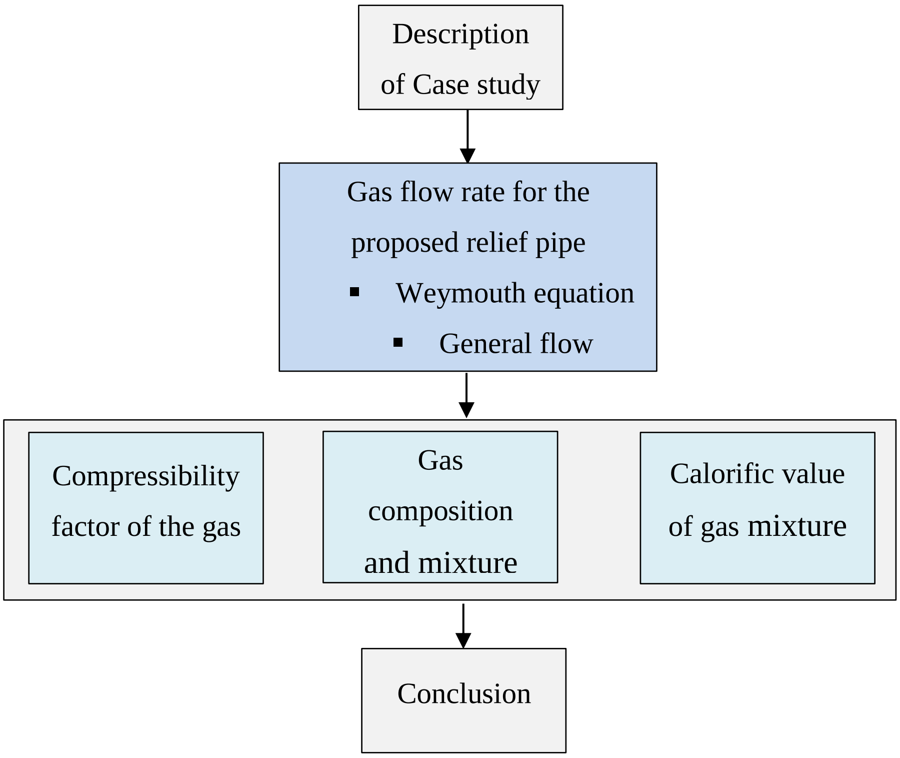


Figure 15: Schematic illustration of the chapter analysis sequence

3.1 Description of the case study

The existing gas supply chain in the Nigerian gas industry suffers from exogenous interruptions causing a limited supply to the power plants and other consumer nodes. With over 200 trillion cubic feet (TCF) of the gas reserve, only about 0.5 percent is commercialised presently through LNG per annum. Unlike natural gas liquefaction with massive investment in the value chain for export commercialisation, the domestic and regional market’s natural gas supply chain is impacted by limited infrastructure. When the limited infrastructure is interrupted, downtime, shortage of supply, and loss are unavoidable. This case study policy driver for the sustainable gas supply chain provides gas majorly to consumers as a domestication policy target. The policy driver is significant due to the incremental demand from the power sector to stimulate the multiplier effect of gas in the domestic economy and guarantee long-term energy security. Stochasticity or demand uncertainty can be considered from the perspective of other consumers but not necessarily power plant consumers where supply in the proposed case study is deterministic and identified to be below demand level for all periods.

For single pipeline flows, pressure and flow rate or gas composition are easy to address. However, when considering a more extensive transmission system with a network of interconnected pipelines, pressure change during interruption or composition in one part of the network influences capacities and flows in other parts of the network; thus, taking a system perspective of the decision processes is critical. The case study involves three gas streams that converge in a single node. The system includes a single processing plant, four compressors in a single compressor station, two main pipelines, one natural gas company represented by a city gate station, and three different consumers. The contractual volume obligation for power plant consumers is 360 mmscfd. It is assumed that this demand should be met monthly for the entire planning horizon. The values of the case study are analysed over a 30-month planning horizon. Data collected can be found in appendix 1. Reference parameters used within the time horizon are shown in table 8 in chapter four. The peculiarity of the problem is that the case study does not include dedicated storage, yet prolonged interruptions occur. The steady and transient states are both examined for the reviewed study.

3.2 Gas flow rate

Generally, the gas flow rate (Q) depicts is the amount of gas that passes from one node to another which can be estimated using different flow equations. In Menon [68], gas flow rate and pipeline throughput are used interchangeably. To determine the flow rate in a gas pipeline, a composition of different physical characteristics like the properties of the gas, pipe length, diameter, pressure, temperature, and pressure drop caused by friction in the pipeline is analysed [68]. However, there are typically no standard flow rates for natural gas. According to Menon [68], the prediction of flow rates is possible if pipeline size, length, inlet, and outlet pressure of pipe nodes are known. Various formulas have been developed to calculate pipeline transportation performance as a function of gravity, compressibility factor, and gas properties over the years. Therefore, the calculations in subsection 3.1.1 will show the relationship between the various factors mentioned to determine the proposed alternative pathway's flow rate.

For the case study under consideration, the gas properties presented in section 3.4 in mole fraction are subsequently converted to mass fraction to calculate the gas heating value. The gas temperature affects the flow rate in the gas pipeline, and the constant temperature process is isothermal such that $\Delta T_g = 0$. Although researchers have studied flow rate and pressure drops in a steady state, Ke and Ti [131] argued that because the transient state is encountered mostly in a real-life situation, the use of steady state conditions is less favourable. To this end, it is important to analyse and compare the pipeline flow rate in both steady and transient states. Therefore, to determine the flow rate of the proposed lateral relief pipeline, it is essential to ascertain the best possible additional capacity required to mitigate the effect of an interruption on each of the relevant gas supply chain nodes.

3.2.1 Flow equation for relief pipeline

The pipeline flow equation is used to determine the gas flow rate, based on the principle of flow analysis of gas in pipes [82]. Though the pipeline gas flow can be affected by different factors, the relationship between the inlet and outlet pressure can be analysed using different equations. Different flow equations have been provided to calculate the gas flow rate, but in this study, only the Weymouth equation is used due to its application for high pressure, high flow rate, and large diameter pipelines. A standard unit of the U.S. Customary System (USCS) is applied for the pipeline flow equation in this work.

The Weymouth equation in Menon [68] calculates the gas flow in the pipeline by estimating the pressure drop. It is the most moderate flow equation that predicts the highest pressure drop; it then becomes useful to use the equation to determine the worst-case pressure drop in the gas pipeline. It is introduced to calculate the gas flow in the pipeline as a function of inlet and outlet pressure. The flow rate must equal the proportional capacity for expansion based on the additional pathway introduced in the case study. Weymouth is for pipeline 12 inches in diameter and 32.19 km equivalent of 20 miles in length, as established in Menon [68]. It is also ideal for branch-off and trunk lines. Here, we can assume that the relief pipeline diameter size is ≤ 12 inches. If the elevation effect is neglected, the flow can be calculated using the USCS unit thus:

$$X_{kz} = 433.5E \text{ x} \left(\frac{T_b}{P_b}\right)\left(\frac{P_{in}^2 - e^s P_{out}^2}{G T_f L_e Z}\right) 0.5 \text{ x } D^{2.667} \tag{3.1}$$

X_{kz} = gas flow rate through the horizontal pipeline segment (k, z)

$P_{in} P_{out}$ = inlet and outlet pressures (psi) respectively

where:

P_{in} = Upstream pressure, psi

P_{out} = Downstream pressure, psi

Z = Compressibility factor, dimensionless
T_f = Average gas temperature, °R (460 + °F)
D = Pipeline diameter, NPS (inch)
L = Pipeline length, miles
G = Pipe gravity, measure at molar mass divided by molar mass of air
S = Specific gravity, elevation adjustment parameter, dimensionless
E = Efficiency, a decimal value less than or equal to 1
f = Friction factor, dimensionless
T_b = Base temperature, °R (460 + °F)
P_b = Base pressure, psi

The gas pipe gravity is vital so that the hydrocarbon gas density is calculated as the ratio of the gas molar mass (molecular weight) to the molar mass of air (molecular weight of air) with a known value of 28.94. The given molar mass of the case study is 18 (see table 5), the pipe gravity is calculated as 18/28.94 = 0.62. Gas gravity is in the range of 0.55 to 1.5, with a default gravity value of 0.65. For the sweet or dry gas, the gravity is given as 0.55, while 1.5 gravity is for the sour or wet gas. Using the ideal gas law, we first assume that the compressibility factor is 1, which means that no deviation of the real gas from the ideal gas. The standard base temperature in °R is given as (460 + °F).

Using Equation 3.1, the calculated flow rate for the additional pipeline pathway using the Weymouth equation is as follows:

$$X_{kz} = 433.5 \text{ x } 0.95 \text{ x} \left(\frac{60 + 460}{14.7}\right)\left(\frac{1400^2 - 600^2}{0.62 \text{ x } (75 + 460) \text{ x } 15 \text{ x } 1}\right) 0.5 \text{ x } 12^{2.667} \tag{3.1.1}$$

Flow rate = 197.02 mmscfd

A higher gravity means a heavier gas, which implies a lower flow rate, while a lower gravity means lighter gas, which implies a higher flow rate. For instance, a higher flow rate of 202.29

mmscfd is achieved when the gravity is reduced from 0.62 to 0.59. For reference, see equation 3.1.3. Also, increased pipeline length will reduce the flow rate. For instance, when the length of the pipeline increased from 15 miles to 19.8839 miles (equivalent of 32 km), and gravity remains at 0.62, the flow rate was reduced. The reduced flow rate also applies if the gravity is reduced, and the pipeline length is increased. For reference, see equation 3.1.4.

$$X_{kz} = 433.5 \text{ x } 0.95 \text{ x} \left(\frac{60+460}{14.7}\right)\left(\frac{1400^2-600^2}{0.62 \text{ x } (75+460) \text{ x } 19.8839 \text{ x } 1}\right) 0.5 \text{ x } 12^{2.667} \tag{3.1.2}$$

Flow rate =171. 40 mmscfd.

$$X_{kz} = 433.5 \text{ x } 0.95 \text{ x} \left(\frac{60+460}{14.7}\right)\left(\frac{1400^2-600^2}{0.59 \text{ x } (75+460)\ x\ 15\ x\ 1}\right) 0.5 \text{ x } 12^{2.667} \tag{3.1.3}$$

Flow rate = 202.29 mmscfd.

$$X_{kz} = 433.5 \text{ x } 0.95 \text{ x} \left(\frac{60+460}{14.7}\right)\left(\frac{1400^2-600^2}{0.59 \text{ x } (75+460) \text{ x } 19.8839 \text{ x } 1}\right) 0.5 \text{ x } 12^{2.667} \tag{3.1.4}$$

Flow rate = 175.70 mmscfd

In the equations above, each component of the pipeline characteristics affects the pipe’s flow rate. For instance, using the Weymouth equation, if the pipeline increases from 15 miles to 19.8839 miles (the equivalent of 32 km), the flow rate decreases from 202.29 mmscfd to 175.70 mmscfd even with the same gravity value. All approximated values obtained here fall between the lower and upper limit of the proportional capacity for expansion. For further explanation, see chapter four.

3.2.2 General flow equation

The General Flow Equation (GFE) for the steady state isothermal flow in a gas pipeline is introduced, which is the basic equation for involving the pressure drop with flow rate. It means that the pressure drop can be determined in a steady state. The GEF is also called the Fundamental Flow equation (FFE). Just like the Weymouth equation, the flow rate (Q) using the GFE also depends on the gas gravity, pressure, and compressibility factor (z-factor or *Z*). The gravity, pressure, and compressibility factor are inversely proportional to the throughput (gas flow rate). Usually, the flow rate determined using the Weymouth equation is compared with the flow rate using the GFE after considering the Reynolds number and the transmission factor. For a smaller diameter pipeline, the smaller the size, the lower the flow rate. On the other hand, the larger the diameter, the larger the flow rate. If the inlet pressure at the upstream is constant in the steady state, the flow rate will increase if the downstream outlet pressure is reduced. There is pressure drop P1 > P2 when friction between the gas flowing in the pipe and the pipe walls occurs.

$$X_{kz} = 77.54 \text{ x} \left(\frac{T_b}{P_b}\right)\left(\frac{P_{in}^2 - P_{out}^2}{GT_f LZf}\right) 0.5 \text{ x } D^{2.5} \tag{3.2}$$

where:

Q=gas flow rate, measured at standard conditions, ft3/day (SCFD)

f=friction factor, dimensionless

Pb=base pressure, psi

Tb=base temperature, °R(460+°F)

$P1$=upstream pressure, psi

$P2$=downstream pressure, psi

G=gas gravity, (air=1.00)

Tf=average gas flowing temperature, °R (460+°F)

L=pipe segment length, miles

Z=gas compressibility factor at the flowing temperature, dimensionless

D=pipe inside diameter, inches.

3.2.3 Partial pressure

The gas flowing through the pipe is a mixture of multiple sources. The total pressure of two or more gases mixed in equal amounts depends on the total number of gas particles present. The total pressure will simply be the sum of the partial pressure of each gas. The ideal gas law assumes that all gases behave identically, and this has been adopted for the gas mixture in this work. Simple gas pressure can be directly proportional to the number of moles present if volume and temperature are held constant. The following formulas can be adapted depending on the number of gas supply sources.

For a single gas, the pressure can be written as:

$$\mathrm{P} = \mathrm{n}\left(\frac{\mathrm{RT}}{\mathrm{V}}\right) = \mathrm{n}^{\mathrm{x}}\,\mathrm{constant} \tag{3.3}$$

Here, the gas pressure is directly proportional to the amount of moles present, assuming volume and pressure are held constant.

For a mixture of two gasses, the pressure can be written as:

$$\mathrm{P_{tot}} = \mathrm{P_A} + \mathrm{P_B} = \mathrm{nA}\left(\frac{\mathrm{RT}}{\mathrm{V}}\right) + \mathrm{nB}\left(\frac{\mathrm{RT}}{\mathrm{V}}\right) = (\mathrm{nA} + \mathrm{nB})\left(\frac{\mathrm{RT}}{\mathrm{V}}\right) \tag{3.4}$$

Here, the gas pressure of gas A and B will be twice the pressure of each component.

For a mixture of n component (more than 2)

$$\mathrm{P_{tot}} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{n1}\left(\frac{\mathrm{RT}}{\mathrm{V}}\right) \tag{3.5}$$

Here, the total pressure is the sum of all the partial pressures of the n components such that $\mathrm{P_{tot}} = (P_1 + P_2 + P_3 + \ldots. + P_n)$.

3.3 Compressibility factor

The compressibility factor, also known as the deviation factor, is the ratio of deviation of real gas from ideal gas such that the real gas volume is less than the ideal gas volume. By definition, the compressibility factor is the ratio of the volume the gas occupies at a given pressure and temperature to the volume it would ordinarily occupy in an ideal situation [15]. It is also a function of gas gravity, temperature, and pressure and not the gas quantity. At standard conditions of 15°C or 60°F temperature and 14.5 psi atmospheric pressure, the compressibility factor is approximately 1. To future explain it, the compressibility factor or deviation factor is close to 1 at low pressures and high temperatures such that the real gas behaves almost precisely as the ideal gas under these conditions.

The ideal gas equation:

$$Pv = nRT_g \tag{3.6}$$

The real gas law equation:

$$Pv = ZnRT_g \tag{3.7}$$

where:

P= absolute pressure (psi), T_g= absolute temperature, *R* = gas constant, *Z* = compressibility factor, *v*= volume, *n* = number of moles of the gas. When the natural gas goes through the refinery plant, it is expected that the processed gas has little or no impurities, therefore we assume that the gas mole is 100 percent methane and the R universal gas constant with a value of 10.732 psi ft3/lb mole °R in USCS units. The real gas law is a modified version of the ideal gas law after the compressibility factor has been considered. To determine the compressibility factor of the close section of a gas pipeline during the shutdown, the gas flowing temperature and the average pressure in the pipe section must be first determined. The upstream pressure is represented as the maximum pressure, while the downstream pressure is represented as the minimum pressure. There are different methods available in the open literature to calculate the compressibility factor at different gas temperature (T_g) and pressure (P). The formula below is used to determine the mainline average pressure.

$$P_{avg} = \; {}^{2}\!/_{3} \left[P_1 + P_2 - \frac{P_1 P_2}{P_1 + P_2}\right] \tag{3.8}$$

where:

$P_1 = 1100\,psi, P_2 = 700\,psi$

$P_{avg} = 914.814 psi$

for arithmetic average

$AP_{avg} = 900\,psi$

If the gas is not 100 percent methane but a composition of hydrocarbons majorly with less than 5 percent of non-hydrocarbon, then the gas is said to be sweet or dry gas. The z-factor or Z of the gas from the data provided and analysed in the spreadsheet in Table 2 can be calculated to determine the gas gravity. The compressibility can also be calculated with the molar mass using the previous gas gravity.

Table 3: The gas component spreadsheet in mole fractions

Component	Chemical formula	Mole fraction (Mf)	Mole (Mol)	Molecular weight (Mw)
Methane	CH_4	0.788	16.0423	12.641
Ethane	C_2H_6	0.105	30.0688	3.157
Propane	C_3H_8	0.046	44.0953	2.028
N-Butane	C_4H_{10}	0.009	58.1218	0.523
Iso-Butane	C_4H_{10}	0.008	58.1218	0.465
N-Pentane	C_5H_{12}	0.003	72.1483	0.216
Iso-Pentane	C_5H_{12}	0.003	72.1483	0.216
N-Hexane	C_6H_{14}	0.002	86.1748	0.172
N- Heptane+	C_7H_{16}	0.001	100.2013	0.100
Water	H_2O	0.003	18.0152	0.054
Oxygen	O_2	0.00	-	-
n-octane	C_8H_{18}	-	-	-
Carbon dioxide	CO_2	0.026	44.0095	1.144
Nitrogen	N_2	0.006	28.0134	0.168
Hydrogen-Sulphide	H_2S	0.000	34.0808	0.000
Total		1.000		20.884

The molecular weight of the sample calculated with respect to the mole fraction is 20.884. It is important to state that the molar mass is the same as the molecular weight. Consequently, to determine the gas gravity, the molecular weight is then divided by the molar mass of air given as 28.94. Therefore, using the molecular weight to determine the gravity G= 20.884/28.94 = 0.72. The application of the new gravity calculated to determine the flow rate is shown below.

$$X_{kz} = 433.5 \text{ x } 0.95 \text{ x} \left(\frac{60+460}{14.7}\right)\left(\frac{1400^2 - 600^2}{0.72 \text{ x } (75+460) \text{ x } 19.8839 \text{ x } 1}\right) 0.5 \ \text{ x } 12^{2.667} \tag{3.9}$$

Flow rate = 159.05 mmscfd

For a more accessible and easy equation to calculate the compressibility factor, the California Natural Gas Association (CNGA) method is used, with a temperature of 60 °F and an average pressure of 914.814 psi. The z-factor is calculated based on an average pressure at the inlet and outlet nodes on the main pipeline during the shutdown. The calculated compressibility factor here is for the mainline pipeline only.

$$\frac{1}{\sqrt{Z}} = 1 + \frac{P_{avg} 344{,}400(10)^{1.785G}}{{T_f}^{3.825}} \tag{3.10}$$

where:

P_{avg}: average gas pressure in psi

T_f: average gas temperature, °R (460+°F)

G: Gas gravity (air = 1.00)

Using the gravity of 0.72, to solve for compressibility factor:

$$\frac{1}{\sqrt{\mathrm{Z}}} = 1 + \frac{914.814 \times 344{,}400 \times (10)^{1.785 \times 0.72}}{520^{3.825}} \tag{3.10.1}$$

Z = 0.90

Using the gravity of 0.62 which is closer to the default value, to solve for compressibility factor:

$$\frac{1}{\sqrt{\mathrm{Z}}} = 1 + \frac{914.814 \times 344{,}400 \times (10)^{1.785 \times 0.62}}{520^{3.825}} \tag{3.10.2}$$

Z = 0.93

At this point, to determine the compressibility factor for the relief pipeline, the same formula is applied, but the average pressure will change.

$$\frac{1}{\sqrt{\mathrm{Z}}} = 1 + \frac{1053.33 \times 344{,}400 \times (10)^{1.785 \times 0.62}}{520^{3.825}} \tag{3.10.3}$$

Z = 0.92

The above solution shows how the compressibility is affected by gas gravity and the average pressure. The higher the gravity, the larger the deviation from the ideal gas, also the higher the average pressure, the larger the deviation from the ideal gas. Therefore, applying the compressibility factor of 0.92 in the flow equation to calculate the flow rate for the additional pipeline pathway using the Weymouth equation:

$$X_{kz} = 433.5 \text{ x } 0.95 \text{ x} \left(\frac{60 + 460}{14.7}\right)\left(\frac{1400^2 - 600^2}{0.62 \text{ x } (75 + 460) \text{ x } 15 \text{ x } 0.92}\right) 0.5 \text{ x } 12^{2.667} \tag{3.10.4}$$

Flow rate: = 205.74 mmscfd

3.4 Gas composition and mixture

The natural gas is extracted essentially from associated and non-associated reservoirs at standard pressure and temperature (P, T_f) consists of a mixture of hydrocarbon and non-hydrocarbon gaseous substances. The function of the natural gas mixture is affected by the concentration of heavier hydrocarbons. A typical gas component constitutes methane and other impurities such as ethane, propane, and butane. Based on its composition, natural gas could be grouped as sweet or sour gas, dry or wet gas. The sour or wet natural gas contains a significant amount of hydrogen sulphide and carbon dioxide, which causes rust in the pipeline. For the gas to be sweet or dry, it is required to be processed by a gas refining plant to meet the available pipeline transportation standard. Natural gas processing in the refining plant avoids a significant amount of hydrogen sulphide and carbon dioxide from the sour or wet gas by removing associated hydrocarbons to meet the available pipeline transportation standard for consumers' needs. The processing brings the gas to almost entirely methane when it is dry, and when all other associated hydrocarbons are removed [30].

As natural gas production field composition varies, its properties and behaviour are best known by understanding the behaviour of the constituents [24]. The composition of the natural gas can be reported in terms of mole fraction (mole percentage), mass fraction (weight percentage), or volume fraction (volume percentage). Two essential and useful concepts used to characterise the composition of a mixture are the constituents' mole fraction and mass fraction. In this work, the data is represented in mass fraction before applying the balance equations because of the limitation of reporting gas in volume fraction. The average composition of natural gas as given by the Quality Guidelines for Energy System Studies [132], where the natural gas composition is presumed to be mostly consistent, as shown in Table 4. However, Table 5 displays the chemical composition of the three streams for the case study in both mole and mass fractions. The associated gas field (AGF), non-associated gas field (NAGF), and liquefied natural gas (LNG) import are three sources used in this work. In the AGF, the gas is an associated product and sometimes treated as a by-product. The NAGF are dedicated fields for exploring and utilising natural gas for domestic use and export. Natural gas import is introduced in the gas mixture equation when internal supply is insufficient or as a stopgap measure to forestall shortages when there is system breakdown.

Table 4: Natural Gas composition [132]

Component		Volume
Methane		93.1
Ethane		3.2
Propane		0.7
Butane		0.4
Carbon dioxide		1.0
Nitrogen		1.6
GHV^a (MJ/scm)	38.46	
NHV^b (MJ/scm)	34.71	
a Gross Heating Value		
b Net Heating Value		

Table 5: Chemical composition of gas from three stream sources in mole fractions

Component	Chemical formula	AGF (mole fraction)	NAGF (mole fraction)	Import (mole fraction)	Mixed mass fraction	Property (hydrocarbon)
Hydrocarbon						
Methane	CH_4	0.788	0.847	0.921	0.6031	Light
Ethane	C_2H_6	0.105	0.058	0.052	0.1373	Heavy
Propane	C_3H_8	0.046	0.022	0.021	0.0870	Heavy
N-Butane	C_4H_{10}	0.009	0.006	0.005	0.1494	Heavy
Iso-Butane	C_4H_{10}	0.008	0.004	0.000	0.0232	Heavy
N-Pentane	C_5H_{12}	0.003	0.003	0.000	0.0000	Heavy
Iso-Pentane	C_5H_{12}	0.003	0.003	0.000	0.0000	Heavy
N-Hexane	C_6H_{14}	0.002	0.003	0.000	0.0000	Heavy
N- Heptane+	C_7H_{16}	0.001	0.003	0.000	0.0000	Heavy
Water	H_2O	0.003	0.000	0.000	0.0000	Heavy
Oxygen	O_2	0.00				
n-octane	C_8H_{18}					
Non-hydrocarbon						
Carbondioxide	CO_2	0.026	0.013	0.000		
Nitrogen	N_2	0.006	0.034	0.001		
Hydrogen-Sulphide	H_2S	0.000	0.007	0.000		

3.5 Calorific value of the natural gas mixture

Pipeline gas is typically bought and sold based on fuel heating value [15] produced by burning the gas. If the gas combustion goes beyond the power plant specification range, then the gas quality is low because it will adversely affect the gas power plant engine. The heating value of natural gas depends on its accumulations, influenced by the amount and types of gases they contain. The gas industry always uses the gross heating value (frequently called higher heating value) in custody transfer. This calorific value (CV) is the measure of heating power when the gas is combusted under a specified condition, and this is dependent on the composition of the gas. Because natural gas has a composition of hydrocarbon and non-hydrocarbon chemical compounds, the precise composition of gas determines the amount of heat produced; therefore, its calorific value or heating capacity is not constant.

Simple and quick measurement of the calorific value is done in the pipeline using chromatography. The calorific value can then be ascertained once the various hydrocarbons are separated, and each proportion ascertained. There are two types of calorific values: gross heating value (GHV) and net heating value (NHV). The gross heating value or higher heating value is the total amount of heat generated when a unit quantity of fuel is burnt entirely in oxygen, and the product of combustion is condensed to room temperature. In custody transfer, the gas industry uses the gross heating value. The net heating value or lower heating value is the heat produced when a unit quantity of fuel is burnt entirely in oxygen, and the products of combustion are liberated.

The calorific value of each fuel source is computed based on the percentage mass composition of carbon, hydrogen, oxygen, and Sulphur for combustion. The standard calorific value of natural gas lies between 34-50 MJ/m^3. Pipeline gas is often sold based on its heating CV produced during combustion (see Fig.15). The difference between the values of the GHV and NHV is the heat of water condensed at stated conditions. Therefore, water is a steady product of combustion, and the GHV or NHV is the amount of heat liberated during the combustion of a unit of gas fuel.

Table 6: Data representation: the chemical properties of Natural gas [30]

Properties	Value (mole fraction)
Carbon content (C_1), weight %	73.3
Hydrogen content (H_2), weight %	23.9
Oxygen content (O_2), weight %	0.4
Nitrogen content (N_2), weight %	2.4
Relative molar mass	18.0
Methane number	69-99
Boiling point, ˚C	-162
Relative density, 15˚C	0.72

Given the composition of the gas field in Table 6, the following chemical properties are extracted:

$$\left.\begin{array}{ll} \text{Carbon (C)} & = 0.733 \\ \text{Hydrogen (H)} & = 0.239 \\ \text{Oxygen (O)} & = 0.004 \\ \text{Nitrogen (S)} & = 0.024 \end{array}\right\} \quad \text{Mole fraction}$$

The calorific heating value was calculated by converting the gas composition from mole fraction to mass fraction, using a basis of 100 moles:

Carbon (C) = 73.3 moles * 12 g/mole = 879.6g (3.11)

Hydrogen (H) = 23.9 moles * 1 g/mole = 23.9 g (3.12)

Oxygen (O) = 0.4 moles * 16 g/mole = 6.4 g (3.13)

Sulphide (S) = 2.4 moles * 14 g/mole = 33.6 g (3.14)

The sum of the mass fraction must equal 1 represented thus:

$$\sum_{i=1}^{N} m_i = m_{tot}; \sum_{i=1}^{N} w_i = 1 \qquad \text{Where; } w_{i=} \frac{m_i}{m_{tot}} \tag{3.15}$$

Therefore:

C	= 0.932	O	= 0.007
H	= 0.025	S	= 0.036

Table 7: The chemical properties of three streams and gas mixture in their mass flow rates

Properties	Value-Associated (mass fraction)	Value-non-Associated (mass fraction)	Value-Import (mass fraction)	Mixed mass fraction
Carbon content, weight	0.9320	0.9276	0.9597	0.9234
Hydrogen content, weight	0.0250	0.0096	0.0043	0.0667
Oxygen content, weight	0.0070	0.0117	0.0056	0.0029
Sulfur content, weight	0.0360	0.0511	0.3040	0.0071

Using the Dulong heating formula, the approximate heating value is calculated as:

Gross heating value (GHV):

$$[33{,}800\ C + 144{,}000\ (H - O/8) + 9{,}270\ S)]\ \text{KJ/kg} \qquad (3.16)$$

Putting above values in the formula

$$GHV = [33{,}800 \times 0.932 + 144{,}000\ (0.025 - 0.0070/8) + 9{,}270 \times 0.036]$$
$$= 35{,}309.32\ \text{KJ/kg} = 35.31\ \text{MJ/kg}$$

Net heating value (NHV):

$$NHV = GHV - 9 \times H_2 \times 2466 \qquad (3.17)$$
$$= 35{,}309.32 - 9 \times 0.025 \times 2466$$

Putting above values in formula

$$NHV = 34{,}\ 752.47\ \text{KJ/kg} = 34.75\ \text{MJ/kg}$$

Summarised below is the mass heating calorific value for the three streams and their mixture:

Table 8: Gross and net calorific heating values

Heating	Associated	Non-Associated	Import	Mixed
Gross Heating Value (GHV)	35.3	33.0	33.3	38-40
Net Heating Value (NHV) GHV_a (MJ/m3) NHV_b (MJ/m3)	34.8	32.8	33.1	36-39.3

Description:

The source supply involves three streams of gas mixture; stream 1 is represented by gas field 1, stream 2 represented by gas field 2, and stream 3 contains one import source. The various sources of each gas field mole composition in a stream are the same, and the mass composition for each stream is calculated if the mole composition is known. Optimal CV of the gas mix:

$$Gmi_{\text{stream1}} = Gm_i\ (\text{field1}) = \sum Gm_i\ (\text{well1} + \text{well2} + \text{well3}) \tag{3.18}$$

$$Gmi_{\text{stream2}} = Gm_i\ (\text{field2}) = \sum Gm_i\ (\text{well1} + \text{well2} + \text{well3}) \tag{3.19}$$

$$Gmi_{\text{stream3}} = Gm_i\ (\text{Import}) \tag{3.20}$$

$$GV_{\text{pipe}} = \sum Cf_1\ Gm_i\ (\text{stream1} + \text{stream2} + \text{stream3} \ldots + \text{streamN}) \tag{3.21}$$

where the contribution factor =

$$CF = \frac{\text{mass supplied by stream}}{\text{total mass}} \tag{3.22}$$

A multicomponent mixture of gasses composed of N_1 of stream_1, N_2 of stream_2, N_i.........

The mass fraction of stream1, x1 is defined as the fraction of the total mass in the system that is in stream1:

$$X1 = \quad N_i / N_1 + N_2 + \ldots\ldots N_i \quad = N_i / N_{tot} \qquad (3.23)$$

The mass fraction of each given component in each mixture is the ratio of the mass of the given component to the mass of the entire mixture.

$$N_1 / N_{tot} = \quad N_1 : N_{tot} \quad = 1 \qquad (3.24)$$

Therefore, to get the optimum calorific value of the gas mix, the weighted average of the calorific heating value of three streams of gas will be calculated thus:

$$\text{CVstreamN} = \frac{\text{mig1(CVstream1)+mig2(CVstream2)+mig3(CVstream3)}}{\text{total CV}} \qquad (3.25)$$

where: *mi* = mass rate composition of fields 1 & 2 in streams 1 & 2 and import, g= natural gas, and CV = heating value of each gas stream. Fig. 16 is a pictorial representation of the gas mixture with air for combustion to determine the heating levels of all the gas streams.

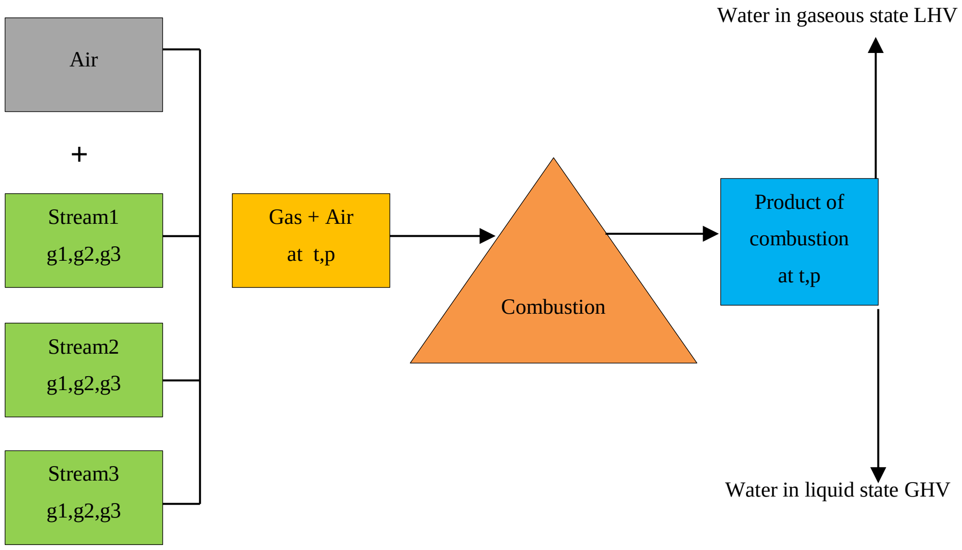


Figure 16: Interaction of the gas mixture in a combustion unit

3.6 Conclusion

This chapter has outlined the characteristics of the reference supply chain under study. The case study description for the natural gas supply chain is presented in this chapter. The role of gas gravity, pressure, and length of the pipeline as significant parameters that determine the calculated gas flow rate of the proposed lateral alternative pathway is analysed. The calculations have shown that the lower the compressibility factor, the higher the flow rate in the relief pipeline. The change in flow rate change means that the compressibility factor is a function of pressure and temperature for the given gas composition. The gas compressibility is lower when the inlet pressure of the relief pipeline is high because as gas from the upstream continues to flow when the outlet valve is shutdown, the shock from the gas flow increases the inlet pressure as the relief pipeline inlet valve is opened during the shutdown. The flow rate can be further increased with lower gravity. Based on the estimated proportional capacity for the relief pipeline, both compressibility factors of 1 and 0.92 provide a flow rate above 200 mmscfd.

This chapter also highlights the multiple streams of supply from the start of the supply chain, indicating that as each production field has a distinct gas composition that can vary with time, the gas commodity supply is also non-uniform. The multi-commodity flow makes the problem difficult to solve and gives rise to even more severe system effects.

This chapter has shown that for the studied case, although natural gas is supplied from multiple sources, the gas quality effect from impurities in the gas composition on the pipeline flow rate calculated is within the required heating value for mixed sources. Therefore, in ensuring the gas quality from the mixture of different material input sources, the CV of the gas mixtures is weighted to obtain an optimum CV within the required range. The equations are calculated on the case study gas network with a mainline pipe diameter of 32 inches, the inlet pressure of 1100 psi, and a standard temperature of 60°F. For simplification, the gas temperature is uniform for all periods in all scenarios. However, the proposed relief line diameter is put at 12 inches with an average pressure of 1053.33psi, accommodating the proportional capacity to meet the desired flow rate.

Chapter 4

Foundation of the Analytical Model

4.1 Model description

The developed model defines the relationship between variables, parameters, and the objective function. The model considers shutdowns of a natural gas supply chain network caused by interruptions beyond the control of the plant operators. The model also considers emission losses resulting from the disruption and the accommodated capacity for expansion in the midstream of the gas network by introducing the lateral relief pipeline. In the case study already introduced in chapter three, continuous flow is expected when the plant is operating unless there is a disruption to the network. The proposed optimisation framework considered for the plant nodes includes (a) disturbance to the flow, (b) alternative pathway to mitigate disturbance and, (c) capacity to expand. The factors in the model also include dependencies identified. The focus is to propose a better functionality of the system in the event of a disruption. The justification of the modelling approach is presented below.

Approach

Mathematical MILP

Method of analysis

Model computation

GAMS 26.14/CPLEX solver

Data

Case study from industry to define the cause and effect

Justification

Versatility and applicability to large/complex & defined optimisation problems

Exhibit well-defined solutions

Ideal tool that suit the research objectives

Allows for quick modification of changes

Process/energy systems and transportation

4.2 Plant shutdown

An overview of a compressor plant shutdown and the impact on existing gas flow from the upstream is described in this section. The likely causes of unplanned or emergency shutdowns are caused by disruptions which include human attack on infrastructure, shortfall in inventory and wear and tear on existing infrastructure. Methane is released into the environment bringing about recorded natural gas losses when a compressor station shutdown. When this shutdown occurs, the main valves from the pipeline to the compressor station are closed. Generally, during a compressor plant shutdown, the remnant of high-pressure gas within the compressor and connected piping between isolation valves is emitted into the atmosphere, also known as **‘**blowdown’. On average, one blowdown vents 15 Mcf/hr (0.015 Mmscf/hr) gas as emission to the environment. When the compressor is pressurised, the leakage can be up to 0.45 Mcf/hr. Gas can also be emitted because of depressurization at 1.4 Mcf/hr from shutdown compressor through leakages from faulty or improperly sealed isolation valve units. The use of a compressor as a baseload or a peak load compressor is a regular occurrence. The baseload compressor is operational in a yearly cycle most of the time and has only 500 hrs downtime on average. However, the peak load compressor is operational for approximately 4000 hrs in a year. It is turned on and off as many as up to 40 times in a yearly cycle.

Based on the impact of the disruption on the flow rate, the developed model is expected to derive an optimum gas flow rate relative to the cumulative capacity constraint during the periods under review, making it a combination of a planning and operation problem. Emission loss is accounted for as well as loss reduction after optimisation. Apart from the losses incurred during the plant node(s) shutdown, there are also startup and shutdown emissions, which means that frequent shutdowns will result in more emissions through losses. Based on existing research and substantial amounts of data collected, a resilient process optimisation strategy on the transmission echelon will provide the required result for such complex process integration. Therefore, this research has narrowed the disruption between the gas plant and compressor station of the studied gas supply chain.

4.3 Description of the alternative pathway

The relief pipeline represents the redundancy that creates the alternative pathway in the proposed workflow design. When the shutdown is introduced, the extra flow line transports the excess gas between the valve and the compressor station, which previously is emitted through a relief valve to the environment, resulting in a loss and emission. The proposed relief pipeline serves both as a flow line and a line packing for the initial trapped gas and gradually flows to a sale line or another compressor station, depending on the proximity to the sale line. The process adopted is to absorb the shocks by following a sequence to reduce the emissions. The identified emergency shutdown is located midstream between the gas processing plant and the distribution centre for this work.

The resultant effect of shutting down an affected plant node accumulates gas between the valves and the plant node. The excess or trapped gas is stored only for a short while when there is a closure. As natural gas continues to flow from upstream, the gas will stop packing up against this closure, but the already packed gas must be accounted for by the operators. However, the current procedure emits the trapped gas through a relief valve. The immediate action requires that the inlet valve between the pipeline and the affected plant node is shutdown, but operators make provision for a worst-case such that there is an unhindered flow of gas in the pipeline until the valve is completely closed. The introduced pipe guarantees continuous flow and supports the network to withstand the disruption impact.

Change in pressure ΔP affects the gas density and drives flow from the pipe. The flow is usually forward; if a reverse flow is introduced, the pressure at the end of the pipe is greater than the inlet pressure, and the operators are netting the gas flow in two opposite directions. The introduction of a relief pipeline is to reroute the excess flow during the plant node shutdown. This redundancy ensures the pressure at the end does not increase excessively. However, this is subject to time (shutdown), volumes (usually emitted within the period), and pressure of the volume, where the excess gas is accumulated. The model developed in this chapter explains this scenario in detail, and the established technical constraints are necessary conditions for the optimisation process.

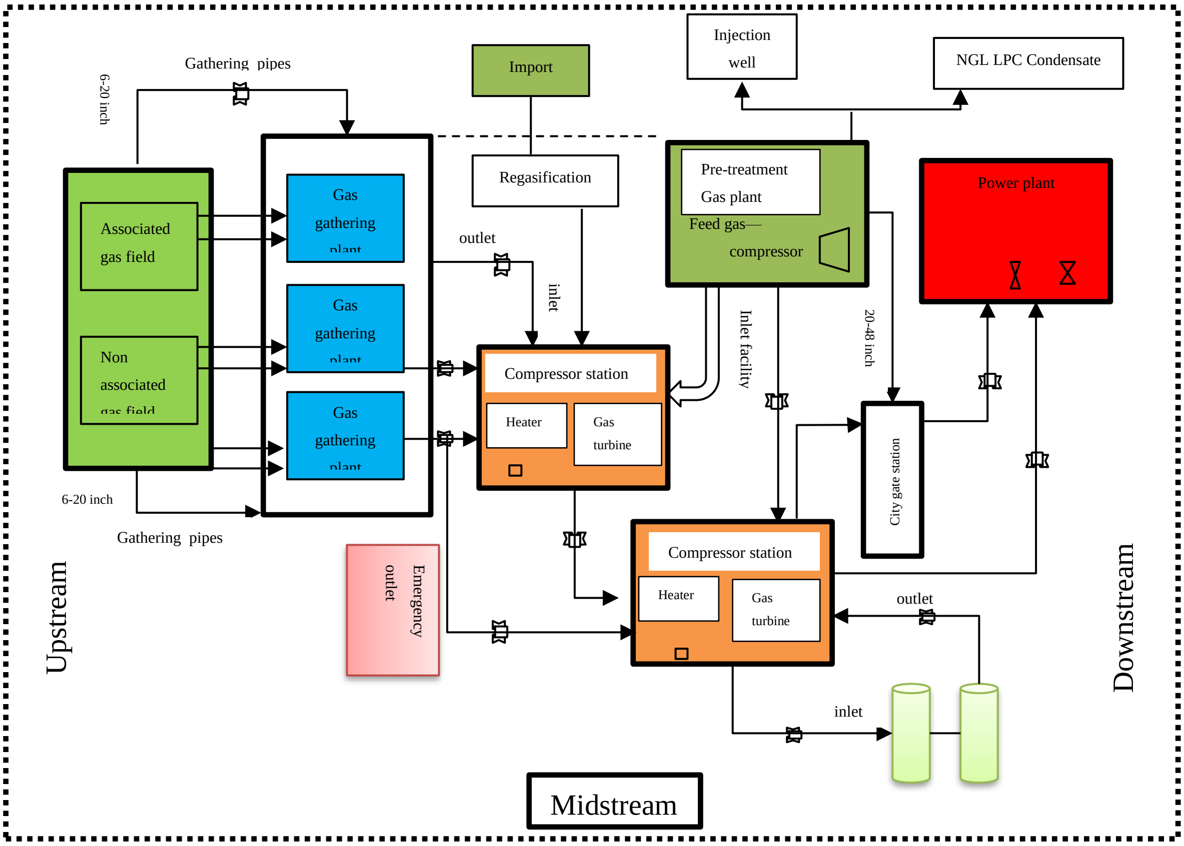


Figure 17: Case study: schematic overview layout of the gas network understudy

Fig. 17 is a detailed overview of the case study network where the relief pipeline represented as an emergency outlet is introduced in the supply chain as an alternative backup pathway during a disruption. For a complex system like the gas network, the linear equation is easier to manipulate and solve; therefore, it is useful to approximate complex systems like the gas network using linear equations. The linearity of the problem will determine the global optimality of the solution. The optimal solution is the feasible solution or best possible value that optimises the objective function. For a daily period in a steady state situation, gas flow behaviour can be described adequately. Cumulative evaluation of the process supply chain, system layout, medium-term production, transmission, and distribution planning is considered in the optimisation [53]. The formulation of the mathematical model constraints is based on existing models formulated in Hamedi et al.; Tomasgard et al. [16,72]. However, the dynamics of the flow are analysed using the same model developed in chapter four.

4.4 The optimisation framework

The first step is to define the system boundaries in the optimisation problem to ensure that all subsystems that affect the system performance are included. A MILP model is formulated to optimise the natural gas supply chain using a mathematical modelling mitigation approach to achieve resilience. The total planning horizon is for a period of 30 months, represented as t. All identifiers, which include sets, parameters, and variables, must first be declared to develop the model. A detailed explanation is found in subsequent subsections. The mathematical formulation enables the additional workflow design of the system and the capacity for expansion during a shutdown. The optimisation framework process presented in Fig. 18 is, therefore, divided into constraints and objective function expressed as:

Maximise: $\boldsymbol{f}(|\boldsymbol{x}|)$ (function to be optimised)

subject to: $|\boldsymbol{g}|(|\boldsymbol{x}|)$ ≥ or ≤ 0 (m inequality constraints)

and $|\boldsymbol{h}|(|\boldsymbol{x}|)$ = 0 (p equality constraints)

In the studied problem, all sets are represented by nodes in the supply chain. Each node represents each plant in the supply chain relevant for this study. The scope of the model is defined to reduce complexity but reflects a real-world problem. Fig. 18 displays the optimisation framework for the studied problem which shows the steps taken in the optimisation process. The initial step is defining the study’s objective function based on identified parameters and decision variables. The parameters and variables are used to form the constraints or equations that serve as inputs in the model. Initial output is obtained when the simulation is run. It is projected that the proposed solution algorithm will not produce the expected final optimised solution until suitable mass flow rates, pressure, and flow constraints are introduced after several iterations. Therefore, the flow constraint, adjusted mass flow rate, pressure, and the relief pipeline as a backup flow line are subsequently introduced in the model. The simulation is run multiple times until an optimised solution is achieved. If the desired optimised result is not achieved from the initial simulation result, the process is initiated after all required parameter adjustments are introduced.

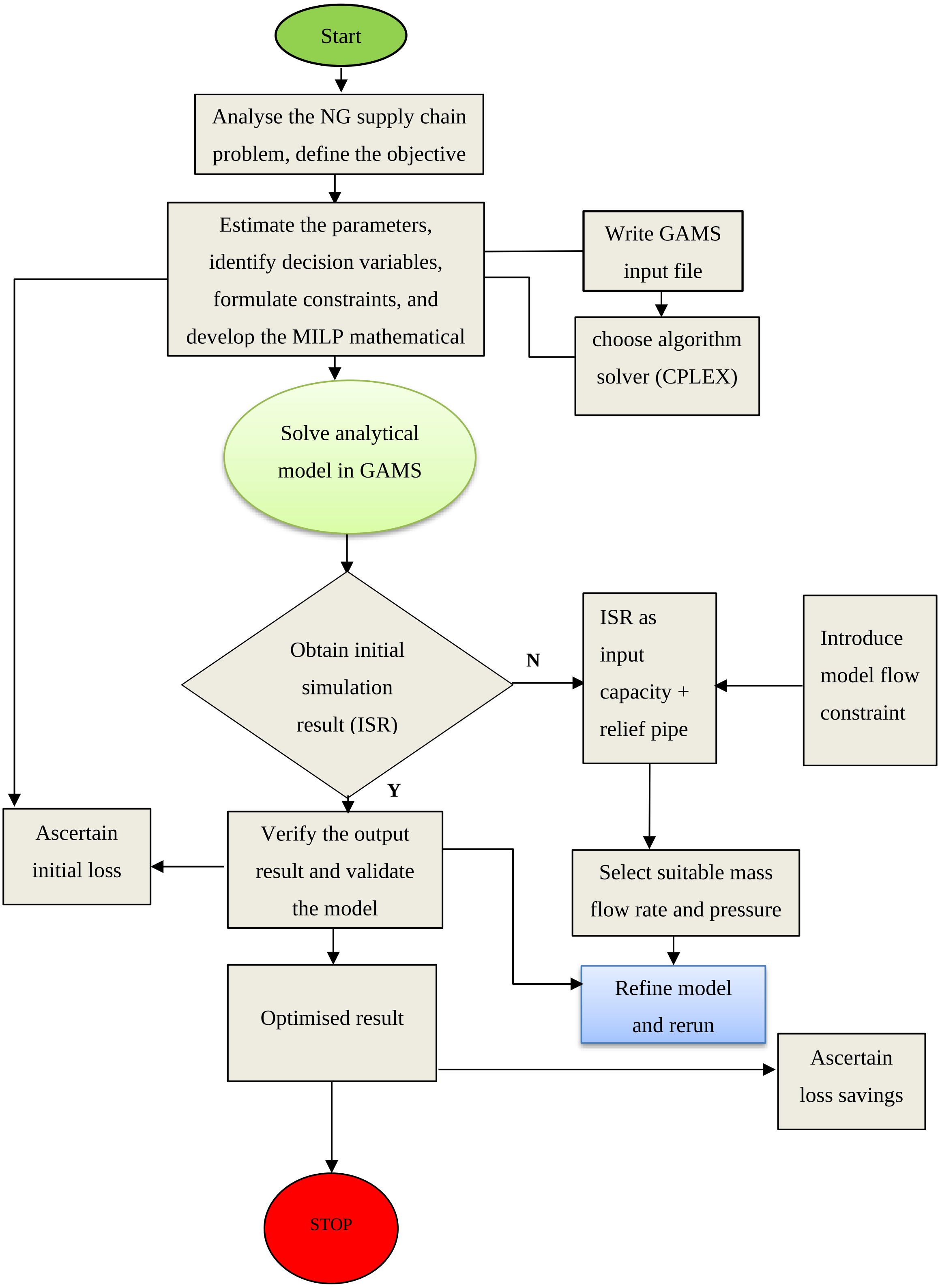


Figure 18: Optimisation process framework

The process framework involves the systematic planning of the steps taken to solve the optimisation problem. From the optimisation framework in the diagram above, the key steps required for the analysis of a problem is elaborated as follows:

Analyse and define the problem, define the objective. At the start of the process, the first step of the research is to analyse the problem to be studied. After preliminary investigation, the studied problem will also use the defined objectives and limitations in light of the problem. The results of this step are a clear grasp of the need for a solution and an understanding of the nature of the problem.

Estimate the parameters, identify decision variables, formulate constraints, and develop MILP mathematical model. The activities that constitute this step are the information, the parameters, the data, the decision variables, and the identified constraints required to formulate the model in the form of equations. The model is then formulated as an input file in the chosen software programming language (GAMS) and solver.

Obtain initial simulation result (ISR). An initial result without redundancy is derived when the analytical model is run in GAMS. This result is re-introduced as an input and then the proposed workflow is modelled for optimisation which gives room for capacity for expansion which is estimated based on the capacity of the existing mainline to accommodate the trapped gas between the closed inlet and outlet nodes. the problem is solved iteratively till each iteration moves closer to the optimum solution and the desired result obtained. To ensure a robust model, all critical nodes in the supply chain will be analysed over the planning horizon.

Verify the output result and validate the model.
The solution to the problem is obtained with the assistance of the model and the right data input. Such a solution is not implemented immediately but is used to test the model and to find any limitations. If the solution is not reasonable, updating and modification of the model are considered at this stage with the modification of mass flow rate and pressure. The result of this step is the optimised solution that meets the set-out objective(s).

4.5 The mathematical programming model

The mathematical optimisation modelling tool adopted in this work is known as the GAMS. It is a mathematical programming system for optimisation which supports interfaces with several optimisation algorithms or solvers. The model comprises the different sets of equations, combining both the objective function(s) and the constraints to develop the model. The formation of the equations is a combination of sets, parameters, and variables. The GAMS program consists of one or multiple statements that define data structures and data modifications. The declaration of each symbol is necessary before use with assigned values before being referenced in the assignment statement. GAMS is considered a reliable optimisation tool for mathematical modelling of the supply chain, where the run time varies based on the objective to be achieved. Some literature supporting the use of GAMS for supply chain optimisation can be found in Tabkhi et al.; Azadeh and Raoofi; Azadeh et al.; Kazemi and Szmerekovsky; Liu [28,67,133–135]. A simple flowchart is introduced in organising the GAMS program, highlighting how it is modelled (see appendix 3).

The execution of the problem formulation is run on GAMS 26.14 with the CPLEX solver 12 in an intel ® core ™ i7 and a zero-optimality to achieve a suitable solution for this supply chain problem using the case study provided. The justification for the use of this modelling optimisation tool is because it allows for the quick introduction of changes in the model specifications, provides a high-level language for the apt description of complex models, allows model descriptions that are independent of solution algorithms, and also allow statements of algebraic relationship that are explicit [136].

4.5.1 Model assumptions

Generally, some assumptions are made concerning all relevant identified nodes in the studied supply chain. Since the research intended to analyse the impact of disruption on the transmission level which has a direct consequence on the throughput, the listed assumptions simplify the studied problem. The model is defined in terms of the following assumptions:

- The time horizon is divided into equal time intervals $t\epsilon T$. Problem is timebound.
- The inlet nodes include a set of suppliers, processing plant, compressors, and city gate nodes $S\epsilon\{i = j = k = g\}$.
- The supply of refined product from compressor $k\epsilon K$ to power plant consumer $m\epsilon M$ is below the contractual agreement.
- The shutdown and startup of periods $t\epsilon T$ are defined for every plant k. During shutdown period t there is a loss of gas from blowdown valves Z_t^E. The startup is defined as the time the plant starts running featured as $Y(kt)$ after a shutdown featured as $R(kt)$ while the operating time is represented as $X(kt)$.
- A set of demand volumes for household and industrial represented as d_{nt}^b and d_{qt}^c.
- A set of demand volumes for power plant represented as d_{mt}^a however, with a dedicated power plant capacity rc_{mt}^{max}.
- During the shutdown $R(kt)$, loss Z_t^E through emission is recorded for a time duration.
- The impact on the flow into the plant during the disruption is bounded by the minimum S_k^{min} and maximum S_k^{max} mass flow rates.
- Each node from the supplier to the consumers are connected. There are no dedicated storage units, but the pipelines are used temporarily for storage and can only accommodate a certain amount of product for every given time.
- It is projected that not more than two nodes are simultaneously shutdown.
- The supply chain of interest consists of centralised nodes.
- Disruption to the network nodes is the primary cause for the shortfall in supply.
- All parameters are assumed to be deterministic with linear dependencies.
- Problem is time bound
- The initial state of the network is static except for the introduced redundancy.
- All assumptions are within acceptable boundaries.

For all period, the optimisation should make the following critical decisions:

- Introduce capacity for expansion to the system.
- The operating status of the plant node includes operating, shutdown, and startup.

4.5.2 Set Definition

The set definition involves the set declaration and initialisation. Sets are known as identifiers and are building blocks for the GAMS model that allows for easy read of the model. Firstly, the sets are declared and then placed in the appropriate condition. Every set is represented by letters and has elements or members, as shown in Table 9 below. Also, to begin the set statement, the set keyword is used, and the arithmetic notations are referred to as the set elements. The comprehensive set used for this model is shown below.

Table 9: Set declaration nomenclature

Superset	Set names & mathematical notation
i	set of all suppliers, $i \in I$, $\{I = 1,2,3 \ldots . I\}$
j	processing plant producer, $j \in J$, $\{J = 1,2,3 \ldots . J\}$
k	compressor plant transmission, $k \in K$, $\{K = 1,2,3 \ldots . K\}$
g	city gate station, $g \in G$, $\{G = 1,2,3 \ldots . G\}$
m	power plant consumer, $m \in M$, $\{M = 1,2,3 \ldots . M\}$
w	gas storage $w \in W$, $\{W = 1,2,3 \ldots . W\}$
q	industrial consumers, $q \in Q$, $\{Q = 1,2,3 \ldots . Q\}$
t	periods in time, $t \in T$, $\{T = 1,2,3 \ldots . T\}$
p	pipeline, $p \in P$, $\{P = 1,2,3 \ldots . P\}$
z	relief pipeline, $z \in Z$, $\{Z = 1,2,3 \ldots . Z\}$
n	domestic/commercial consumer $n \in N$ $\{N = 1,2,3 \ldots . N\}$

Superscripts:

Max = maximum

Min = minimum

+ = inlet

− = outlet

Off = offline

On = online

4.5.3 Parameters

Parameters are known values used in the model also known as identifiers. The parameters declared in Table 10 is an addition to the summarised referenced parameters for the case study presented in Table 11. The mass flow rate $\Delta\boldsymbol{m}/_{\Delta\boldsymbol{t}}$ is the measure of the mass of substance passing a node per unit time:

Table 10: Parameter declaration nomenclature

g_i^{max}	Maximum mass flow rate from all gas field input *i* at time *t*
h_j^{max}	Maximum mass flow rate of processing plant *j* at time *t*
h_j^{min}	Minimum mass flow rate of processing plant *j* at time *t*
s_k^{max}	Maximum mass flow rate of compressor *k* at time *t*
s_k^{min}	Minimum mass flow rate from compressor *k* at time *t*
rc_{mt}^{max}	Maximum capacity of power plant *m* at time *t*
rp_{zt}^{max}	Maximum relief pipe capacity *z* at time *t*
sc_{it}^{max}	Maximum supply gas fields capacity *i* at time t
jc_{it}^{max}	Maximum processing plant capacity *j* at time *t*
cp_{kt}^{max}	Maximum compressor capacity *k* at time *t*
phi_{gt}^{max}	Maximum city gate capacity *g* at time *t*
pc_p^{max}	Maximum pressure into the pipeline
pc_p^{min}	Minimum pressure into the pipeline
mc_k^{min}	Minimum pressure in the compressor
mc_k^{max}	Maximum pressure in the compressor
$emission_k$	Loss through emission at compressor during the shutdown at time *t*
Δ_k	Number of shutdowns at plant *k* in time *t*
d_{mt}^a	Demand capacity for *m* consumer at time *t*
d_{nt}^b	Demand capacity for *n* consumer at time *t*
d_{qt}^c	Demand capacity for *q* consumer at time *t*
λZ_P	Pipeline diameter
θP_p^{max}	Maximum proportional capacity for expansion
θP_p^{min}	Minimum proportional capacity for expansion
inc_{pt}	Capacity of pipeline *p* before expansion

αU_p	Pipeline pressure at the start
γZ_P	Pipeline temperature at the start and end nodes
ys_{wt}	Initial inventory level
st_{wt}^{max}	Maximum storage capacity
st_{wt}^{min}	Minimum storage capacity
δP_t	Shutdown period
δ_k	Minimum offline period after shutdown of plant node k
Ψ_k	Minimum online time
δZ_k	Total periods plant k have been offline since last operating period
$\Psi \mathrm{P}_k$	Total periods plant k have been continuously online since last startup
ε_k	Compression factor in node k

Table 11: Reference parameters for case study

Symbol	Description	Value	Unit
t	Duration of each time interval	1	days
T	Total number of time in the planning horizon	30	days
d_{mt}^{a}	Demand for gas for consumer m	360	mmscfd
θP_p^{max}	Maximum proportional capacity expansion rate	1.5	rate
θP_p^{min}	Minimum proportional capacity expansion rate	1.3	rate
inc_{pt}	Capacity of plant p before expansion	400	mmscfd
δ_k	Minimum offline time	2	days
O_k	Maximum offline time after the shutdown of plant k	52	days
Ψ_k	Minimum online time after the startup of plant k	4	days
S_k^{max}/S_k^{min}	Max/Min flow rates	300/200	mmscfd

4.5.4 Variables

These are primarily unknown factors that need to be optimised, as such, controllable aspects of the problem. It is recommended to declare a variable before it is referenced, just like the set or parameter declaration. The positive variable is also called the continuous or non-negative variable. All positive variables are found in Table 14. The main variables used in the variable statement are shown in Table 12: while binary variables are shown in Table 13. According to [137], the number of times or periods considered will determine the number of binary variables in the model. In essence, for large scheduling horizons, the total number of binary variables can reach prohibitive sizes except if the scheduling process fixes some continuous variables. It will significantly reduce the binary space of the model by ignoring the associated binary variables.

Table 12: Basic variables

Type	Description	Lower bound	Upper bound
Integer	This variable only takes integer values between the bounds	0,1	+inf
Positive	It is from 0 to infinity with no negative bounds	0	+inf
Binary	This type of variable only takes the values of 0 and 1	0	1
Default	This requires no bounds on variable	-inf	+inf

Table 13: Binary variables

X_{kt}=1	if the plant node *k* is in operation at the beginning; otherwise 0
Y_{kt}=1	if the plant node *k* starts operating; otherwise 0
R_{kt}=1	if the plant node *k* stops operating; otherwise 0
H_{zt} =1	if plant node *z* operates when plant node *k* is shutdown; otherwise 0
PI_{jk}=1	if a flow from node *j* to node *k*; otherwise 0
PI_{kz}^{-}=1	if a flow from node *k* to node *z*; otherwise 0

Decision variables in this optimisation problem are the variables whose values vary across the available set of alternatives, increasing or decreasing the objective function value. Here, the decision variables are a combination of upper and lower bound limits, continuous binary, and integer variables. The optimisation is to provide users with a system that meets the required specifications by the engineers.

Table 14: Continuous variables (non-negative)

Z_{ijt}^{A}	gas volume transmitted from nodes i to j in time (t)
X_{jkt}^{P}	gas volume transmitted from nodes $j\ to\ k\ in$ time (t)
Y_{kwt}^{M+}	gas volume transmitted from nodes k to inventory w in time (t)
Y_{wkt}^{M-}	gas volume transmitted from storage inventory to node k in time (t)
Y_{kgt}^{F}	gas volume transmitted from nodes k to g in time (t)
Y_{kmt}^{W}	gas volume transmitted from nodes k to consumer m in time (t)
Y_{gnt}^{P}	gas volume distributed from nodes g to consumer n in time (t)
Y_{gqt}^{C}	gas volume distributed from node g to consumer node q in time (t)
Z_{t}^{E}	total amount of losses
R_{kzt}^{F}	gas flow to relief pipe from mainline during the shutdown at time (t)
δ_{zt}^{inc}	capacity increment at time (t)
S_{kmt}^{T}	gas shortage volume from the compressor to the power plant
B_{wt}^{S}	gas storage level
P_{p}^{in}	pressure at the pipeline inlet node
P_{p}^{out}	pressure at the pipeline outlet node
P_{jkt}^{in}	pressure inlet to compressor node
P_{kzt}^{out}	pressure outlet to relief node
P_{z}^{Bar}	pressure in the relief pipe
L_{kt}^{T}	monthly loss target at the compressor

4.6 Constraints

These are the required conditions for acceptable results that provide the relationship between decision variables and parameters. Optimisation problems usually have variables constrained by the variable function $f(x)$ to be optimised. The minimisation or maximisation of a given function within reasonable limits of the given constraints is determined by constrained optimisation. Going by Collette and Siarry [78] description of constrained optimisation, the variables of the function to be optimised are constrained so that the optimum values is allowed to occur only in a strictly defined search space. These essential constraints are constructed from variable combinations and implemented at specific points over the time interval period. This work addresses a multiple criteria problem to reflect a real-world problem. Therefore, there are multiple constraints to the objective function(s), and all equations are represented as constraints in the model. Appendix 3. summarises all constraints used in this work.

I. Shutdown and startup

The following binaries are presented relating to offline and operating actions of the plant node k and the introduction of the alternative pathway plant node z (relief pipeline). The binaries only take 1 or 0 values. They are introduced to model the resilience of the network.

$X_{(k,t)} = \{1$, if plant node k is operating at the beginning of time t; otherwise 0

$Y_{(k,t)} = \{1$, if plant node k starts operating at time t; otherwise 0

$R_{(k,t)} = \{1$, if the plant node k stops operating at time t; otherwise 0

$H_{(z,t)} = \{1$, if node z operates when plant node k is shutdown; otherwise 0

Accordingly, constraint (1) shows that if node k starts operating at the start of the planning horizon, then $Y(k,t)=1$, and $R(k,t)=0$, but if node k is operating before startup then $X(k,t) = 1$. Therefore, the plant is already in operation. In constraint (2), the simultaneous recognition of startup $Y(k,t)$ =1 and shutdown $R(k,t)$ = 1 action is not allowed. This means that the occurrence of the shutdown is between 1 and -1.

$$Y_{(k,t)} - R_{(k,t)} = X_{(k,t)} - X_{(k,t)-1} \qquad \forall_{k \in K, t \in \mathrm{T}: t=-1} \tag{4.1}$$

$$\begin{aligned} & Y_{(k,t)} + R_{(k,t)} \leq 1 \qquad \forall_{k \in K, t \in \mathrm{T}} \\ & 1 - R_{(k,t)} \geq Y_{(k,t)} \qquad \forall_{k \in K, t \in \mathrm{T}} \end{aligned} \tag{4.2}$$

In constraints (3) and (4), the minimum online time for plant node k after its startup is modelled. It is expected here that the plant will operate for a given period ΨP_k after its startup. The initial state of the plant is represented by ψk with respect to the minimum online time. Here, the total period that plant node k has been operating continuously since its last startup is greater than the minimum online time.

$$X_{kt} \geq \sum_{t^{'}=t}^{t+\Psi_k-1} Y_{kt} \qquad \forall_{k \in K,\ t \in T\ : \Psi_k > 1} \tag{4.3}$$

$$X_{kt} \quad = 1 \qquad \forall_{k \in K, t \in T\ : \Psi P_k - \psi_k :\ \psi_k < \Psi P_k} \tag{4.4}$$

Similarly, the minimum shutdown time Δk of plant node k since after its shutdown is modelled in constraint (5) and (6). This ensures that the total time that plant node k has been shutdown continuously is less than the minimum offline time.

$$1 - X_{(k,t)} \geq \sum_{t^{'}=t}^{t+\Delta_k-1} R_{(k,t)}, \qquad \forall_{k \in K, t \in \mathrm{T}: \Delta_k > 1} \tag{4.5}$$

$$X_{(k,t)} = 0, \qquad \forall_{k \in K, t \in \mathrm{T}: \Delta_k - \delta Z_k : \delta Z_k < \Delta_k} \tag{4.6}$$

Parameter δZ_k denotes the initial state of the plant with respect to the total period that plant node k has been continuously shutdown. This is the total period that plant k has been shutdown continuously since its last shutdown. Additionally, a maximum duration of continuous shutdown time of plant node k is modelled, which causes a shortage of supply.

In constraints (7) and (8), the maximum idle time is the maximum time duration that plant k is switched off continuously after its last shutdown, which is expected to be higher than when plant shutdown $R(k,t)=1$.

$$\sum_{t'=t}^{t-o_k} R_{(k,t)} \le o_{(k)} \qquad \forall_{k\in K, t\in \mathrm{T}} \tag{4.7}$$

$$\sum_{t'=t}^{t-(o_k-\delta Z_K)} R_{(k,t)} \le o_{(k)} - \delta Z_{(k)} \qquad \forall_{k\in K, t\in \mathrm{T}} \tag{4.8}$$

II. Supplier and production capacity constraints

Here the total gas volume from all related gas wells does not exceed the maximum production capacity of gas fields in the supply node i. Constraints (9) and (10) ensure that the supply from the supplier and supply to the production plant is less than or equal to the supply capacity and the production plant capacity.

$$\sum_{j\in J} Z^{A}_{(i,j,t)} \le sc^{\max}_{(i,t)}, \qquad \forall_{i\in I, t\in \mathrm{T}} \tag{4.9}$$

$$\sum_{i\in \mathrm{I}} Z^{A}_{(i,j,t)} \le jc^{\max}_{(j,t)} \qquad \forall_{j\in J, t\in \mathrm{T}} \tag{4.10}$$

III. Compressor capacity constraints

This constraint represents the gas flow from processing plant node j to plant node k. Constraint (11) ensures that the supply from the processing plant to the compressor does not exceed the compressor capacity. To account for the loss during plant disruption, the shutdown of plant node k is taken into consideration when there is a flow from plant j to plant k.

$$\sum_{w\in W} YM^{+}_{(k,w,t)} - YM^{-}_{(w,k,t)} + \sum_{j\in J} X^{P}_{(j,k,t)} - Z^{E}_{(t)} \le cp^{\max}_{(k,t)} \qquad \forall_{k\in K, t\in \mathrm{T}} \tag{4.11}$$

$$\sum_{\mathrm{K}\in \mathrm{K}} \sum_{j\in J} X^{P}_{(j,k,t)} - emissions_{(k,t)} \le cp^{\max}_{(k,t)} \qquad \forall_{t\in \mathrm{T}} \tag{4.12}$$

$$\sum_{m\in M} Y^{W}_{(k,m,t)} + \sum_{g\in G} \sum_{q\in Q} \sum_{n\in N} Y^{C}_{(g,n,t)} + Y^{P}_{(g,n,t)} \le cp^{\max}_{(k,t)} \qquad \forall_{k\in K, t\in \mathrm{T}} \tag{4.13}$$

IV. City gate capacity constraint

Constraint (14) ensures that all gas flow from the compressor station in the transmission pipeline does not exceed the city gate capacity when the city gate station is opened. The city gate is the intermediary consumer which supplies to both industrial and household consumers.

$$\sum_{k\in K} Y^{F}_{(k,g,t)} \le phi^{\max}_{(g,t)} \qquad \forall_{g\in G, t\in \mathrm{T}} \tag{4.14}$$

V. Power plant capacity constraint

For the problem under study, the power plant is the primary consumer, and it is being fed directly from the compressor station. In constraint (15), it is expected that gas flow from the compressor station in the transmission pipeline does not exceed the power plant capacity. The shutdown of node k affects the supply of gas majorly to the power plant consumer.

$$\sum_{k\in K} Y^{W}_{(k,m,t)} \le rc^{\max}_{(m,t)} \qquad \forall_{m\in M, t\in \mathrm{T}} \tag{4.15}$$

VI. Demand constraints

In constraints 16 -18, based on the contractual agreement, for every time period, demand from all consumers should be satisfied according to the following equations.

$$\sum_{k\in K}\sum_{m\in M} Y^{W}_{(k,m,t)} = d^{a}_{(m,t)}, \qquad \forall_{t\in \mathrm{T}} \tag{4.16}$$

$$\sum_{g\in G}\sum_{n\in N} Y^{P}_{(g,n,t)} = d^{b}_{(n,t)}, \qquad \forall_{t\in \mathrm{T}} \tag{4.17}$$

$$\sum_{g\in G}\sum_{q\in Q} Y^{C}_{(g,q,t)} = d^{c}_{(q,t)}, \qquad \forall_{t\in \mathrm{T}} \tag{4.18}$$

VII. Storage constraints

In constraints (19) and (20), the gas sent to the pipeline for storage should be less than or equal to the line packing storage capacity. Represented in constraint (21) are the minimum and maximum inventory storage levels. Constraint (21) indicates that the gas storage must fall between its minimum and maximum limits. The parameter y^{S}_{wt} represents the initial inventory in the storage; the variables Y^{M+}_{kwt} and Y^{M-}_{wkt} represents the inflows and outflows to and from the compressor and to and from the storage. However, there is usually a reserve before the injection of gas into the storage in the pipeline.

$$Y^{M+}_{(k,w,t)} + Y^{M-}_{(w,k,t)} \leq \; st^{\max}_{(w,t)}, \qquad \forall_{k\in K,\; w\in W\; t\in T:\; t=1} \tag{4.19}$$

$$Y^{M+}_{(k,w,t)} \leq \; st^{\max}_{(w,t)} - y^{S}_{(w,t)}, \qquad \forall_{w\in W,\quad t\in T} \tag{4.20}$$

$$st^{\min}_{(w,t)} \geq \; B^{S}_{(w,t)} \; \leq st^{\max}_{(w,t)}, \qquad \forall_{w\in W,\quad t\in T} \tag{4.21}$$

VIII. Mass balance law constraints

The material or mass balance is modelled in constraints (22–24). The consideration is that there is no mass build-up in any node of the system irrespective of possible reactions between the inlet and outlet nodes. It is assumed that the gas is 100 percent methane as the processing plant eliminates all pollutants. For every method studied, each node of the network will be constrained to the mass balance law. Thus, for every node of the network system: $\Sigma flow\ in = \Sigma flow\ out$. In this constraint, the gas transmitted from gas well to gas processing plant should equal the gas transmitted from processing plant to the compressor. The total gas supplied from the processing plant to the compressor should equal the sum of gas from the compressor to the power plant and city gate station minus loss from emissions. Gas supplied from the compressors to the city gate station should equal the gas supplied from the city gate station to industrial and domestic consumers. However, for constraint (21), the line packing storage is considered a net of loss through emission. Therefore, to satisfy this constraint, the loss is subtracted from the gas plant's inflow to the compressor plant.

$$\sum_{i\in I}\sum_{j\in J} Z^{A}_{(i,j,t)} = \sum_{j\in J}\sum_{k\in K} X^{P}_{(j,k,t)} \qquad \forall_{\ t\in T} \tag{4.22}$$

$$\begin{aligned}&\sum_{j\in J}\sum_{k\in K} X^{P}_{(j,k,t)} - Z^{E}_{(t)} + \sum_{w\in W}\sum_{k\in K} Y^{M-}_{(w,k,t)} \\ &= \sum_{\kappa\in \mathrm{K}}\sum_{m\in M} Y^{W}_{(k,m,t)} + \sum_{k\in K}\sum_{w\in W} Y^{M+}_{(k,w,t)} + \sum_{k\in K}\sum_{g\in G} Y^{F}_{(k,g,t)} \qquad \forall_{t\in T}\end{aligned} \tag{4.23}$$

$$\sum_{k\in \mathrm{K}}\sum_{g\in G} Y^{F}_{(k,g,t)} = \sum_{g\in G}\sum_{n\in N} Y^{P}_{(g,n,t)} + \sum_{g\in G}\sum_{q\in Q} Y^{C}_{(g,q,t)} \qquad \forall_{t\in T} \tag{4.24}$$

Constraint 25 is introduced when the relief pipe is fully operating, and the trapped gas has been rerouted.

$$\sum_{j\in J}\sum_{k\in K} X^{P}_{(j,k,t)} - Z^{E}_{(t)} = \sum_{k\in K}\sum_{m\in M} Y^{W}_{(k,m,t)} + \sum_{k\in K}\sum_{g\in G} Y^{F}_{(k,g,t)} \qquad \forall_{\ t\in T} \tag{4.25}$$

IX. Pipeline pressure constraint

Here a simple maxflow restriction is introduced. It is assumed that the distance between the pipeline nodes is limited in length. Constraint (26) represents a steady state where inlet pressure equals outlet pressure. The flow is isothermal in which temperature remains constant when the change in pipeline temperature at start and end nodes $\gamma z = 0$. At the point where $P^{in}_{(p)} \geq \neq \leq P^{out}_{(p)}$, it is no longer a steady state because of the pressure drop or rise.

$$P^{in}_{(p)} = P^{out}_{(p)}, \qquad \forall_{p \in P} \tag{4.26}$$

X. Pressure inequality constraints

In the transient state, constraints (27) and (28) are introduced. The pressure at the outlet node does not exceed the maximum pressure in constraint (27), and in constraint (28), the pressure at the inlet node does not exceed the maximum pressure. For the pressure variation in the relief pipeline, the Weymouth equation in chapter three describes the pressure difference between the flow into the mainline as input pressure $P^{in}_{(jkt)}$ and the relief line as output pressure $P^{out}_{(kzt)}$. In constraint (29), it is assumed that if the relief pipeline is operating, the input pressure of the pipeline going into node k is higher than the pressure of the pipeline going into node z: this means that the pressure from the refinery will be higher than the pressure into the relief pipeline. The pressure difference is because of the disparity in the capacity of the relief pipeline size compared to the mainline pipeline. However, if the relief pipeline is the same capacity as the mainline, then the inlet pressure into node k will be lesser than the outlet pressure from node k into node z.

$$P^{out}_{(k,z,t)} \leq Pc^{\min}_{(p)}, \qquad \forall_{\, k \in K, z \in Z, p \in P, t \in T} \tag{4.27}$$

$$P^{in}_{(j,k,t)} \le Pc^{\max}_{(p)}, \qquad \forall_{\, J\in J, k\in K, p\in P, t\in T} \tag{4.28}$$

$$P^{in}_{(j,k,t)}\varepsilon_{(k)} \le P^{out}_{(k,z,t)}, \qquad \forall_{\, j\in J, k\in K, z\in Z, t\in T} \tag{4.29}$$

For each node in the network, the pipeline operates within the maximum and minimum pressure bounds for each period. The pressure in the inlet node must exceed the minimum pressure; also, the pressure in the outlet node does not exceed the maximum pressure as this helps to keep the pressure in check. In constraint (30), for each node in the gas network, the relief pipeline operates within the maximum and minimum pressure bounds for each period. Constraint (31) displays the time there is a flow from j to k and from k to z during shutdown such that a zero (0) flow from either node at a time does not affect the pressure balance. The $bigM$ represents a number which is large enough.

$$Zh^{\min}_{(z)} \ge P^{Bar}_{(z)} \le Zh^{\max}_{(z)}, \qquad \forall_{\, z\in Z} \tag{4.30}$$

$$P^{in}_{(j,k,t)} - P^{out}_{(k,z,t)} + bigM_{(z,t)}(PI^{-}_{(k,z)} - PI_{(j,k)} - 1) \le bigM_{(z,t)} \qquad \forall_{\, j\in J, k\in K, z\in Z, t\in T} \tag{4.31}$$

In the transient state, to understand the pressure movement at both the mainline and the relief pipeline in time series during the shutdown period, constraints (32) and (33) are introduced such that the inlet and outlet pressures are multiplied by the mass flow rates. For the relief pipeline, constraint (33) is within the flow rate of 200 mmscfd based on the proportional capacity for expansion. This is already established in 3.2.1 using the flow equation.

$$P^{in}_{jkt}\; s^{\max}_{k} \ge X^{P}_{jkt}, \qquad \forall_{\, j\in J, k\in K, p\in P, t\in T} \tag{4.32}$$

$$P^{out}_{kzt}\; v^{\max}_{z} \ge R^{F}_{kzt}, \qquad \forall_{\, k\in K, z\in Z, t\in T} \tag{4.33}$$

XI. Capacity expansion constraints

Regarding establishing the capacity for expansion, the cumulative capacity obtained is when the relief pipe is operating and the closed valve at the inlet node is opened. In contrast, the proportional capacity for expansion obtained is when the relief pipeline is operating only. In constraint (34), a lower and upper bound for the cumulated capacity for expansion are introduced on the flow into the relief pipeline. This relief pipeline capacity modified in constraint (35) is by introducing the compression factor. In constraint (36), the proportional capacity for expansion is not more than the capacity before expansion multiplied by the maximum proportional capacity for expansion and is not less than the capacity before expansion multiplied by the minimum proportional capacity for expansion. This is in line with the proportional capacity expansion proposed in [135]. It is assumed that during the shutdown of plant k, the capacity of the plant node increased proportionately to accommodate the stranded gas between the closed valve and the compressor station. The relief pipeline is only operating when there is a disruption to the plant node k.

$$\sum_{p \in P} Inc_{(p,t)} \theta P_{(p)}^{\min} \geq \sum_{k \in K} R_{(k,z,t)}^{F} \leq \sum_{p \in P} Inc_{(p,t)} \theta P_{(p)}^{\max} - Inc_{(p,t)}, \qquad \forall_{z \in Z, t \in \mathrm{T}} \tag{4.34}$$

$$\sum_{k \in K} R_{(k,z,t)}^{F} \varepsilon_{(k)} \leq rp_{(z,t)}^{\max}, \qquad \forall_{z \in Z, t \in \mathrm{T}} \tag{4.35}$$

$$Inc_{(p,t)} \theta P_{(p)}^{\min} \geq \delta Inc_{(z)} \leq Inc_{(p,t)} \theta P_{(p)}^{\max}, \qquad \forall_{p \in P, z \in Z, t \in \mathrm{T}} \tag{4.36}$$

XII. Flow constraints

Constraint (37) ensures emission losses during the shutdown of the compressor plant do not exceed the capacity of the relief pipeline, and this constraint should be ignored if flow to the relief pipeline should only occur when the binary for the relief pipeline = 1. A corresponding upper and lower bound for flow ($s_k^{\min}$, $v_z^{\min}$ and $s_k^{\max}$, $v_z^{\max}$) before and during the shutdown is introduced in constraints (38) and (39).

$$Z_{(t)}^{E} \leq R_{(k,z,t)}^{F}, \qquad \forall_{k\in K, z\in Z, t\in \mathrm{T}} \tag{4.37}$$

$$s_{(k)}^{\min} X_{(k,t)} \leq X_{(j,k,t)}^{P} \leq s_{(k)}^{\max} X_{(k,t)}, \qquad \forall_{j\in J, k\in K, t\in \mathrm{T}} \tag{4.38}$$

$$v_{(z)}^{\min} R_{(k,t)} \leq R_{(k,z,t)}^{F} \leq v_{(z)}^{\max} R_{(k,t),} \qquad \forall_{k\in K, z\in Z, t\in \mathrm{T}} \tag{4.39}$$

Constraint (40) ensures that the relief pipeline only operates when there is a shutdown, while constraint (41) represents when the plant is not running (shutdown) R_{kt} = 1. To ensure that the relief pipeline is operating only when there is a shutdown in the mainline, constraint (42) is introduced. Constraint (43) ensures that the duration the plant is shutdown does not exceed the maximum offline time after shutdown. However, if the relief pipeline operates at all times, then constraint (40) is revised to constraint (44) such that capacity obtained is when the relief is operating for all time t. Constraint (44) explains that the flow of gas to the relief pipe from mainline during the shutdown at time t exceeds when the relief pipeline is operating during shutdown multiplied by the period that plant is continuously shutdown.

$$\sum_{k\in K} R_{(k,z,t)}^{F} \delta P_{(t)} \leq H_{(z,t)}, \qquad \forall_{z\in Z, t\in \mathrm{T}} \tag{4.40}$$

$$IOFF_{CB_{(k)}}^{-} R_{(k,t)} \geq \delta P_{(t)}, \qquad \forall_{k\in K, t\in \mathrm{T}} \tag{4.41}$$

$$R_{(k,t)} = H_{(z,t)}, \qquad \forall_{k\in K, z\in Z, t\in \mathrm{T}, IOFF_{CB_{(k)}}^{-}} \tag{4.42}$$

$$R_{(k,t)} \delta P_{(t)} \leq o_{(k)}, \qquad \forall_{k\in K, t\in \mathrm{T}, IOFF_{CB_{(k)}}^{-}} \tag{4.43}$$

$$\sum_{k \in K} R^{F}_{(k,z,t)} \geq H_{(z,t)} \delta P_{(t)}, \qquad \forall_{z \in Z, t \in \mathrm{T}} \tag{4.44}$$

XIII. Shortage/loss constraints

The flow from the initial node j less the accumulated supply to consumers equals the shortage. Constraint (45) ensures that the actual shortage based on demand from the consumer is determined. The consumer node represented here is the power plant. Here, the shortage relates to time t, and the assumption is that other consumers are fully satisfied.

$$\sum_{j \in J} \sum_{k \in K} X^{P}_{(j,k,t)} - \sum_{m \in M} Y^{W}_{(k,m,t)} + \sum_{g \in G} \sum_{n \in N} Y^{p}_{(g,n,t)} + \sum_{q \in Q} Y^{C}_{(g,q,t)} = S^{T}_{(k,m,t)}, \qquad \forall_{t \in \mathrm{T}} \tag{4.45}$$

Constraints (46-48) ensures that the plant shutdown is for at least t period and the emission multiplied by the shutdown time exceeds the shortage volume but less than the monthly loss target.

$$\sum_{k \in K} \delta_{(k)} emission_{(k,t)} \geq \sum_{m \in M} S^{T}_{(k,m,t)}, \qquad \forall_{t \in \mathrm{T}} \tag{4.46}$$

$$1 - X_{(k,t)} \geq \delta_{(k)} R_{(k,t)}, \qquad \forall_{k \in K, t \in \mathrm{T}} \tag{4.47}$$

$$\sum_{k \in K} emission_{(k,t)} \leq \sum_{k \in K} L^{T}_{(k,t)}, \qquad \forall_{t \in \mathrm{T}} \tag{4.48}$$

4.7 Formulation of the objective function

The objective function is formulated to estimate the fitness of a set of decisions such that the main elements that affect the general performance of the supply chain system are introduced in the optimisation goal. Both single and multiple objective optimisations are popular for supply chain planning, with multi-objective optimisation modelling problems and solution methods being introduced in supply chain management in recent times [135]. In this optimisation problem, decision variables and constraints are also introduced, as suggested by [138].

The overall objective function is to optimise resilience in the gas supply chain system using flow volume flexibility from supplier to consumer nodes. The flexibility of the supply chain nodes will help achieve the targeted resilience and building the resilience will help maintain the flexible outlook of the nodes. The optimisation problem aims to increase natural gas flow to meet consumer's demand and loss reduction during plant shutdown in this work. For simplification, the optimisation ($Ƶ_1$ + $Ƶ_2$) problem has been compressed into a single-objective function. The objective function is expressed as:

$f = Ƶ_1 + Ƶ_2$ which is further expanded as ($f = SVF+PVF+TVF+LES+OS+AF\ldots$)

$$\begin{bmatrix} \sum_{ijt} g_{(i)}^{\max} ZA_{(i,j,t)} \varepsilon_{(k)} + \sum_{jkt} h_{(j)}^{\max} X_{(j,k,t)}^{P} \\ -\sum_{kt} o_{(k)} Z_{(t)}^{E} + \sum_{kwt} s_{(k)}^{\max} Y_{(k,w,t)}^{M+} - Y_{(w,k,t)}^{M-} \\ +\sum_{kgmt} s_{(k)}^{\max} Y_{(k,g,t)}^{F} + Y_{(k,m,t)}^{W} \\ +\sum_{kmt} YW_{(k,m,t)} mc_{(k)}^{\max} + \sum_{kgt} Y_{(k,g,t)}^{F} mc_{(k)}^{\max} \\ +\sum_{kt} \psi_{(k)} Y_{(k,t)} + \delta_{(k)} R_{(k,t)} \\ +\sum_{kzt} v_{(z)}^{\max} R_{(k,z,t)}^{F} + \delta_{(k)} \end{bmatrix} \tag{4.49}$$

In the expression above, the objective function is broken down into aggregate volume flexibility as a function of flow represented as Z_1 and loss savings represented as Z_2. For a better explanation, Z_1 is defined into three volume flexibility functions. The supply node volume flexibility (SVF) is a function of flow from node i to j multiplied by the mass flow rate of the gas field. The processing node volume flexibility (PVF) is a function of node j to k multiplied by the mass flow rate of the processing plant. The transmission node volume flexibility (TVF) is a function of node k to m and g multiplied by maximum pressure in the compressor. This is applicable in both the steady and transient states before the compressor plant shutdown and after the mitigation strategy is introduced. The Z_2 encompasses the loss and emission savings, the operating status of the plant, and the additional flowline.

The supply node volume flexibility (SVF)

$$\sum_{ijt} g_i^{\max} Z_{ijt}^{A} \varepsilon_k$$

This shows the maximum inlet flow from the supplier node to the processing plant node multiplied by the mass flow rate.

The processing node volume flexibility (PVF)

$$\sum_{jkt} h_j^{\max} X_{jkt}^{P}$$

This shows the maximum inlet flow from processing plant node to compressor plant node multiplied by the mass flow rate.

The transmission node volume flexibility (TVF)

$$+\sum_{kgmt} s_k^{\max} Y_{kgt}^{F} + Y_{kmt}^{W}$$

$$+\sum_{kmt} Y_{kmt}^{W} mc_k^{\max} + \sum_{kgt} Y_{kgt}^{F} mc_k^{\max}$$

This shows the maximum inlet flow from the compressor plant node to the consumer node multiplied by the mass flow rate.

Loss and emission savings (LES)

$$-\sum_{kt} o_k Z_t^E$$

The decision variable (Z_t^E) denotes the total amount of losses caused by the shutdown, which is multiplied by the maximum shutdown time parameter (o_k) to optimise for loss.

Operating status (OS)

$$\sum_{kt} \psi_k Y_{kt} + \delta_k R_{kt}$$

This shows the operating status of the plant with respect to the minimum run time after startup and the minimum shutdown time.

Additional flowline (AF)

$$\sum_{kzt} v_z^{\max} R_{kzt}^F$$

The AF supports the flow to relief pipeline from the mainline during shutdown multiplied by the maximum flow rate.

4.8 Capacity utilisation of the disrupted node

In this study, the proposed additional workflow design for the gas network that allows for contingencies transmits trapped gas from the mainline ($M1$) to the sale line ($M2$) with the sale line having an equal capacity as the mainline. The $M1$ and $M2$ have an equal flow rate of 400 mmscfd. However, the cumulative capacity for expansion rate is 1.3 and 1.5 low/high, respectively. The proportional capacity represents the relief pipeline capacity, which is between 120 to 200 mmscfd if the capacity of the mainline is 4000 mmscfd. If the sale line ($M2$) flow rate increases because of gas flow from the relief pipeline without changing the originating pressure, the increased flow rate will cause a pressure drop, which is adjusted with compression in the sale line ($M2$). The capacity utilisation factor in the network is determined when the capacity factor is first calculated at time t at the time when the plant is operating. The formulas for capacity factor, capacity utilisation, and the output gap are presented below:

Capacity factor:

$$\frac{\text{Actual ouput of node p}}{\text{Potential output at full capacity utilisation}} \text{ x time} \tag{4.50}$$

Capacity utilisation is the weighted average of the ratio:

$$\frac{\text{Actual ouput of node p}}{\text{Potential output at full capacity utilisation}} \tag{4.51}$$

Output gap:

$$\text{Capacity utilisation} - \text{Actual utilisation} \tag{4.52}$$

In a transient, the change in pressure:

$$\Delta\mathrm{P} = \mathrm{P}_1^2 - \mathrm{P}_2^2 \quad = \frac{\Delta\mathrm{P}}{\Delta\mathrm{T}} \tag{4.53}$$

In steady state:

$$\text{min} = \text{mout} \tag{4.54}$$

4.9 Optimisation scenario overview

The optimisation scenarios summarised in Table 15 are investigated in subsequent chapters (5 & 6) of this work using the model developed in this chapter. Four different scenarios are examined in the steady state in chapter 5. Firstly, the baseline scenario indicates the starting point to estimate the performance of the plant node k and the flow rate based on available data. The mean throughput of the baseline is the performance limit used to compare the various throughputs both in the steady and transient states. In scenario two, the shutdown is introduced, prompting the closure of the inlet and outlet valves of the mainline. As such, the alternative pathway valve is opened, allowing the flow into the relief pipeline. Scenario three is a combination of extended time sequence at successively equally spaced points and flow constraints. Scenario four comprises the worst-case scenario when the shutdown is introduced without an alternative pathway. The peculiarity of the case study is the absence of a dedicated storage facility. The effect of introducing lower and upper bound limits for temporary storage is modelled in scenario five. In addition to these scenarios is the variation in pressure and flow rate in the transient state demonstrated in chapter 6.

Table 15: Optimisation scenarios

Steady state	Description	Condition
Scenario 1	Baseline	Current performance of the supply chain.
Scenario 2	Introduction of redundancy	Shutdown of plant, relief pipeline operating with no pressure variation.
Scenario 3	Impact of flow constraint	Introduction of upper and lower bounds.
Scenario 4	No relief pipeline	The capacity of the plant is reduced.
Scenario 5	No dedicated storage	The introduction of lower and upper bound limits for temporary storage.
Transient state	Description	Condition
Scenario 1	Variation in pressure and mass flow rate	Trapped gas undergoes pressure variation.
Scenario 2	Inlet and outlet nodes closure	Unexpected pressure build-up.

4.10 Conclusion

The analytical model developed in chapter four provides good conformity to describe the interactions among the identified variables and parameters. This chapter describes the modelling approach, the optimisation framework, and the equations established. The formulation of the mathematical model presented is required to understand the behaviour of the system by transforming the identified problem using mathematical analysis to provide solutions. Also, constraints relevant to the restrictions to the variables such as the allowable pressure and temperature, material flow rate or amount of gas transported, and capacity of the plant, are introduced. Although the research problem is carried out in a deterministic environment, the lack of accurate knowledge on certain parameters results in intrinsic uncertainties that may affect the programming model.

A detailed description of the proposed additional workflow to mitigate the gas supply chain's interruption is also presented in this chapter. The additional workflow and the disruption are modelled in constraints (5-8) and (32-34). The effect of the flow constraints introduced will be determined in chapters five and six when applied to the case study problem. Therefore, the optimisation framework encapsulates the disturbance to the flow and the required mitigation approach. In this work, a demand-driven supply chain problem is formulated as a mixed integer linear programming (MILP) model to prevent the discharge. The formulation of the optimisation model for the gas network is presented by formulating a MILP optimisation model of the gas network. Once formulated, the simulation is run using GAMS/CPLEX solver. All relevant constraints and underlying assumptions are identified. Also outlined in this chapter is the description of all optimisation scenarios according to the expected conditions. The defined conditions of the individual scenarios listed in this chapter and the capacity expansion to satisfy the workflow introduced are some of the uncertainties identified in Chapter four. The effects of these conditions after modelling are further explained in chapters five and six of this work.

Chapter 5

Steady State Analysis During Shutdown

5.1 Optimisation in steady state

This chapter provides the modelling of the studied problem in a steady and deterministic state. The system is in a steady state when the values typifying the gas flow are independent of time. In this state, the model assumes that the process in the plant nodes is stable with zero variation with respect to time, pressure, and temperature. The simplification of the modelling and the assumption of a zero derivative with respect to time makes the steady state modelling more popular [139]; however, unrealistic as the estimation do not represent a true reflection of the state of the plant and the gas flow rate. Sometimes, the initial modelling of the equipment design is realised in the steady state, which is further validated by the transient state to analyse the process behaviour over time, given certain circumstances. The overall target is to observe the change in the improved flow rate. In this work, flow rate and throughput are used interchangeably.

5.1.1 Scenario one: The baseline

The use of baseline is to superimpose the results of the different scenarios so that the reader can visually appreciate the differences and to track improvements made in the planning horizon. The performance level of the compressor (node k) with respect to the corresponding minimum mass flow rate when $X(k,t)$ = 1 and $Y(k,t)$ = 0 is displayed in Fig. 19. This is calculated as a flow constraint of $k1$ to $k4$ by multiplying the minimum mass flow rate by the operating time of the compressor. Node k is defined as a crucial indicator instrumental to the system performance. Increased performance of the compressors is seen towards the end of the planning horizon with $k3$ outperforming $k1$, $k2$, and $k4$. Although none of the compressors reached maximum capacity load, $k1$ and $k4$ are the least performing.

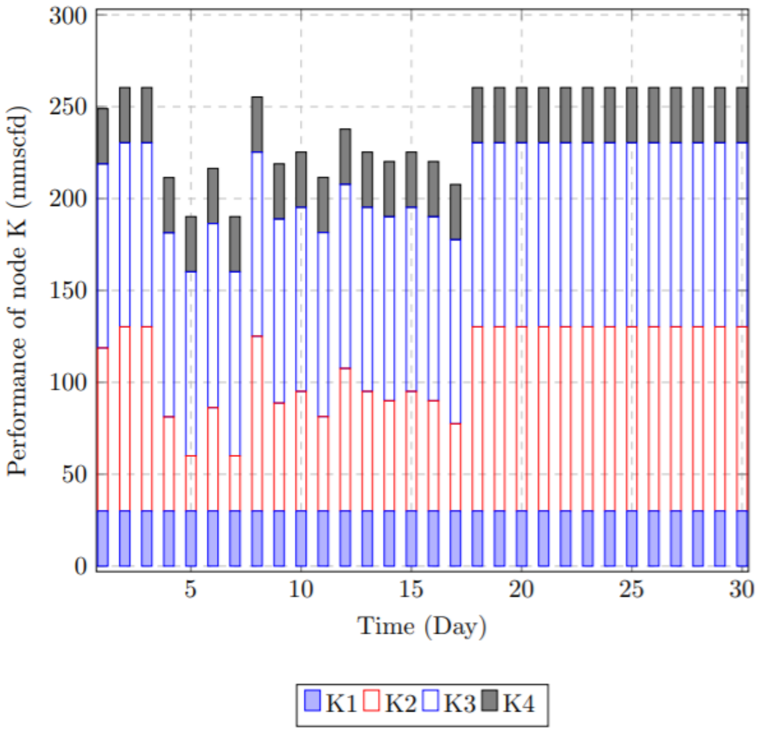


Figure 19: Performance level of compressors at baseline

Since the beginning of the planning horizon, the number of periods that the compressor node has been offline since its last operating period $\delta P_{(t)}$, total number of periods at the beginning of the planning horizon that plant k has been continuously operating since its last startup ΨP_k, total period that plant k have been offline since last operating period δZ_k, and the maximum offline period O_k, is shown in Table 16. For the period under review, the disruption occurs in three different periods at $t8$, $t19$, and $t27$ respectively, over the planning horizon. These shutdown times are based on a percentage shortfall on the baseline performance flow rate.

Table 16: Case study: the initial state of the compressor node

Parameter	Plant				Period		
	$k1$	$k2$	$k3$	$k4$	$t8$	$t19$	$t27$
O_k	52.08	30	30	50	0	0	0
δZ_k	32.08	10	10	30	0	0	0
ΨP_k	10	10	10	10	0	0	0
$\delta P_{(t)}$	1	1	1	1	1	1	1

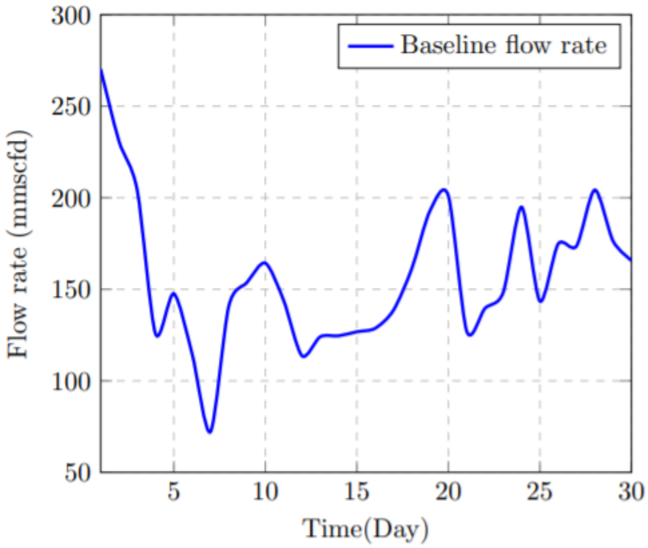
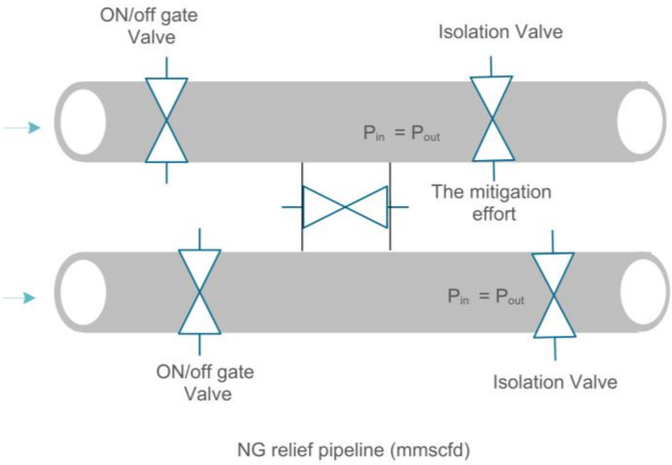


Figure 20: Baseline flow rate at time t for case study

In Fig. 20. the mean flow rate analysed at the start of the planning horizon for all demand is displayed. The analysed mean flow rate of the baseline is 200.38 mmscfd. With a target mean flow of 360 mmscfd per time t, the baseline demand gap flow rate is 159.62 mmscfd. The topology redundancy is introduced as a mitigation strategy to optimise under different scenarios presented in the subsequent sub-sections.

5.1.2 Scenario two: Introduction of topology redundancy

The underlying concept behind the topology redundancy is to satisfy the mitigation effect using a relief pipeline as an alternative pathway. The introduction of the relief pipeline is also known as the shutdown scenario. The conditions to satisfy this scenario is when shutdown is introduced, and no pressure variation is recorded. The additional pathway introduced in the steady state is displayed in Fig 21. In scenario two, the disruption where $R(k,t) = 1$ is added, resulting in the pipeline closure. The computation is made in a deterministic environment where all parameters, constraints, and objective function are known. As such, steady state performance of the supply chain is determined.



$$mass\ flow\ rate = \frac{\Delta m}{\Delta t}$$

Figure 21: Steady state flow in the relief pipeline during shutdown for all period

From the computation, the output of improved flow rates shown in Figs. 22 and 23 is obtained when there is no pressure drop at the inlet and outlet nodes of the pipeline. Each node in the network is within the lower and upper bound limits of the pressure obtained from the case study. The mass balance is introduced for all parameters less loss through emission during compressor plant shutdown.

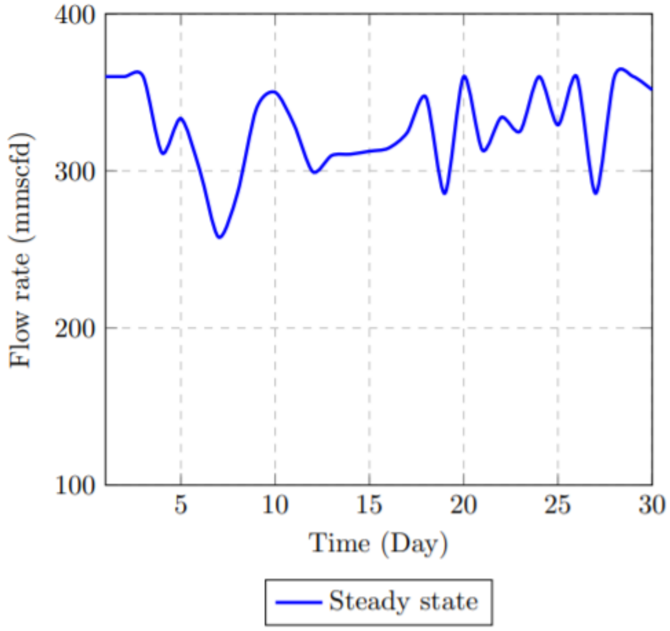


Figure 22: Improved flow without pressure drop

Assuming the number of plant nodes is the same for all operating time in the baseline and shutdown scenario in the steady state, the mean flow rate is then increased from 200.38 to 327.67 mmscfd shown in Fig. 22. The improved flow rate is obtained by relaxing the disruption period such that the shutdown time is defined. The shutdown of the compressor station means that at least one compressor plant $k1$ to $k4$ in the mainline is not operating during the entire shutdown period.

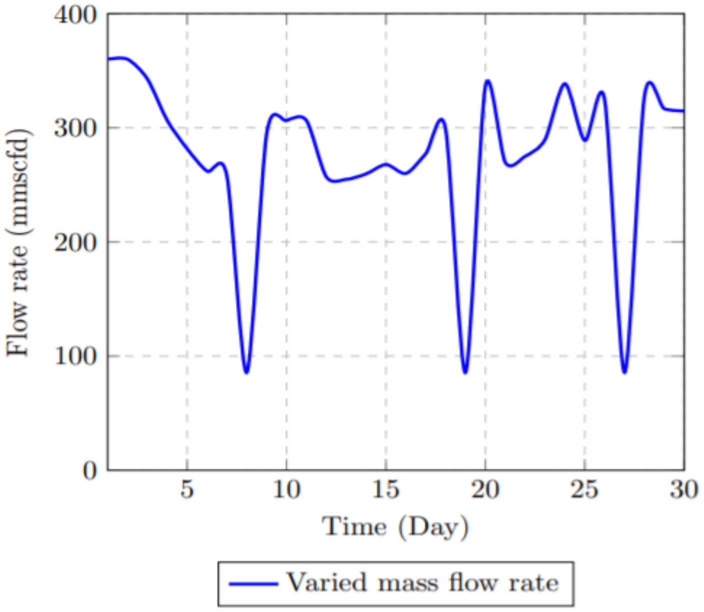


Figure 23: Improved flow without pressure drop at varying capacity rates

At different mass flow rates when the capacity of plant k varies, the optimised flow rate in Fig. 23 indicates a minimal improvement from the baseline to 276.38mmscfd, and the impact of the shutdown can be easily determined. To achieve the results in Figs. 22 and 23, then $X(k,t)$=1 such that the scheduling of supply to consumers comes from one to two compressors at any given time. The diagram displayed in Fig. 24 shows that the improved flow rates in Figs. 22 and 23 can be achieved, when at least one compressor plant is supplying consumers for all periods under review. The performance level of the compressor is also analysed, where $R\_F(k,z,t)$ is operating when $X(k,t)$= 0 and $Y(k,t)$=1 with respect to the corresponding minimum mass flow rate, as displayed in Fig. 25.

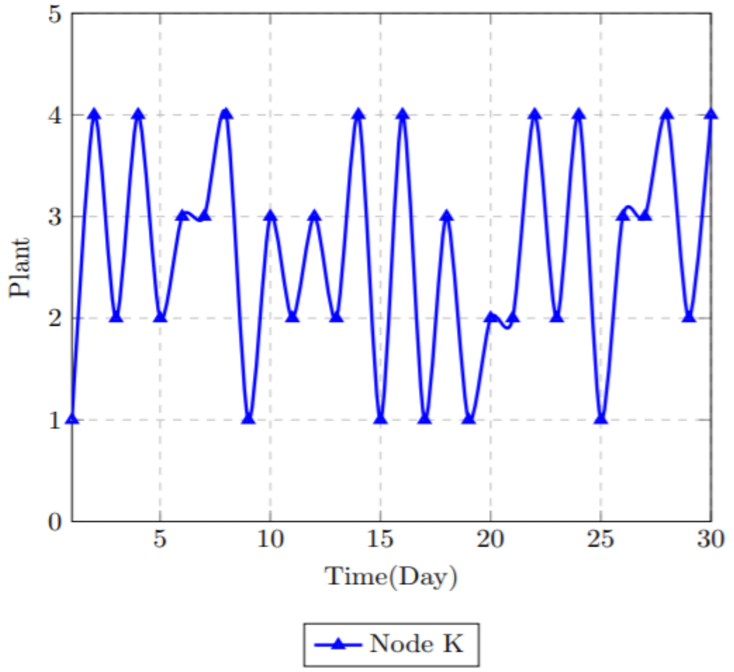


Figure 24: Operational performance of the compressor plant

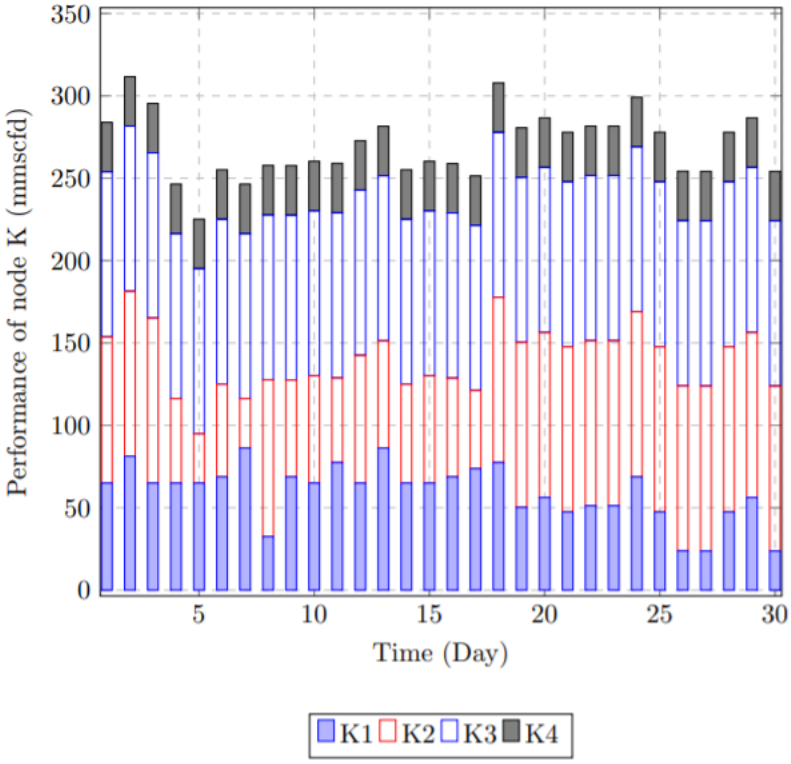


Figure 25: Performance level of the compressor mass flow rate when $Y(k,t)$=1

This is calculated as a flow constraint to compressors $k1$ to $k4$ by multiplying the minimum mass flow rate by the operating time of the compressors. While $k3$ and $k4$ remained unchanged, $k1$ and $k2$ saw an increase in performance as shown in Fig. 25. The output in Table 17 displays different performances, analysed based on flow rates and performance of the initial node(s) in the steady state. In the model, it is expected that input for the initial node will equal output for subsequent nodes such that gas volume transmitted from the gas fields z^{A}_{ijt} equals gas volume transmitted to the processing plant X^{P}_{jkt}.

Table 17: Variation in output performance

Scenario: $Z^{A}_{ijt} = X^{P}_{jkt}$	Offline	Capacity	Mass flow rate (mmscfd)	Final solve
X^{P}_{jkt} =1040	No. of offline increased from 3 to 4	115.79	300/200	6.852488e+7
X^{P}_{jkt} =1040	No. of offline increased from 3 to 6		320/200	6.702802e+7
X^{P}_{jkt} =1040	No. of offline increased from 3 to 5		340/200	6.630019e+7
X^{P}_{jkt} =1040	No. of offline increased from 3 to 6		380/200	6.495804e+7
X^{P}_{jkt} =1040	No. of offline increased from 3 to 8		380/200	5.390145e+7
X^{P}_{jkt} =630	No. of offline increased from 3 to 10		300/200	5.390145e+7

From the displayed Table 17 above, when the maximum mass flow rate is adjusted, the offline time changes as well as the final solution. Therefore, the best possible mass flow rate is shown at maximum of 300 mmscfd and minimum of 200 mmscfd with the least number of times when the plant is not operating. It is also shown that the activities of an initial node affect the performance of subsequent nodes considerably. Further analysis is carried out at the point when the operating status $R(k,t)$=1 in the mainline and when the relief pipeline operating status is $H(z,t)$=1. The output in Table 18 shows that from node k to z, at stable pressure, the higher the mass flow rates, the higher the optimum value.

Table 18: Comparison of output performance from nodes (k) to (z) at a stable pressure

Scenario: $Z^{A}_{ijt} = X^{P}_{jkt}$	Description	Mass flow rate	Final solve
XP =1040	Max. mass flow rate nodes k and z	300/200	7.936451E+7
XP =1040	Max. mass flow rate of nodes k and z	300/300	8.243251E+7
XP =1040	Max. mass flow rate of nodes k and z	340/200	8.258324E+7
XP =1040	Max. mass flow rate of nodes k and z	340/300	8.565124E+7

From the displayed figure in Fig. 26, the impact of the mass flow rate on the shortages for the same period studied shows that the baseline has a higher shortage than the optimised results using the different mass flow rates. For simplicity, only two mass flow rates are compared to the baseline in Fig. 26.

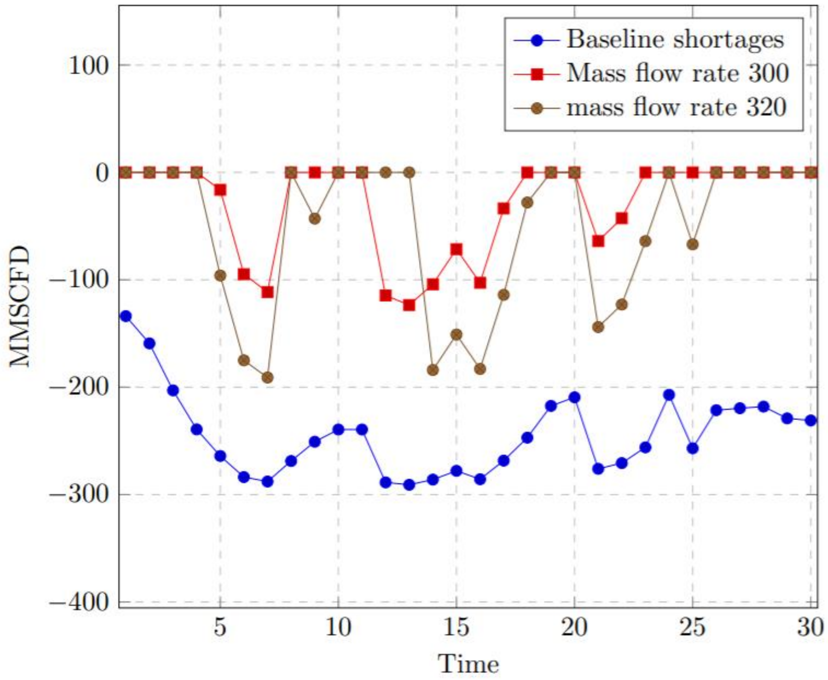


Figure 26: Shortages at baseline and at different mass flow rates

In Table 19, the shrinkage cost of the shortage is calculated. The shortage is obtained when the variance of the gas in the inlet and outlet nodes. It gives an idea of the cost of shortages based on the variance from the required output. At the mass flow rate of 300 mmscfd, the variance is minimised as opposed to a higher mass flow rate.

Table 19: Shortage shrinkage

Shortage	Volume of shortage (MMSCFD)	US$3 per MMBtu (converted to MMSCFD)	US$5 per MMBtu (converted to MMSCFD)	US$7 per MMBtu (converted to MMSCFD)
Baseline	7,326	22,857,603.54	38,096,005.91	53,334,408.27
Flow rate: 300	879	2,742,448.80	4,570,748.00	6,399,047.20
Flow rate: 320	1,564	4,878,329.04	8,130,548.40	11,382,767.76
Flow rate: 340	2,394	7,468,106.88	12,446,844.80	17,425,582.72
Flow rate: 380	4,778	14,908,648.56	24,847,747.60	34,786,846.64

5.1.3 Scenario three: Impact of flow constraint in extended time

Here, the upper and lower bound flow constraints, displayed in constraints (36) and (37), are introduced. The extension of the time series indexed data points ensures that the time sequence has successively equally spaced points. However, the variation with respect to time is assumed to be zero. The time series is extended where the impact of the flow constraint on the flow rate is investigated such that the flow from the processing plant to the compressor is subject to the min/max mass flow rate of the operating status of the plant.

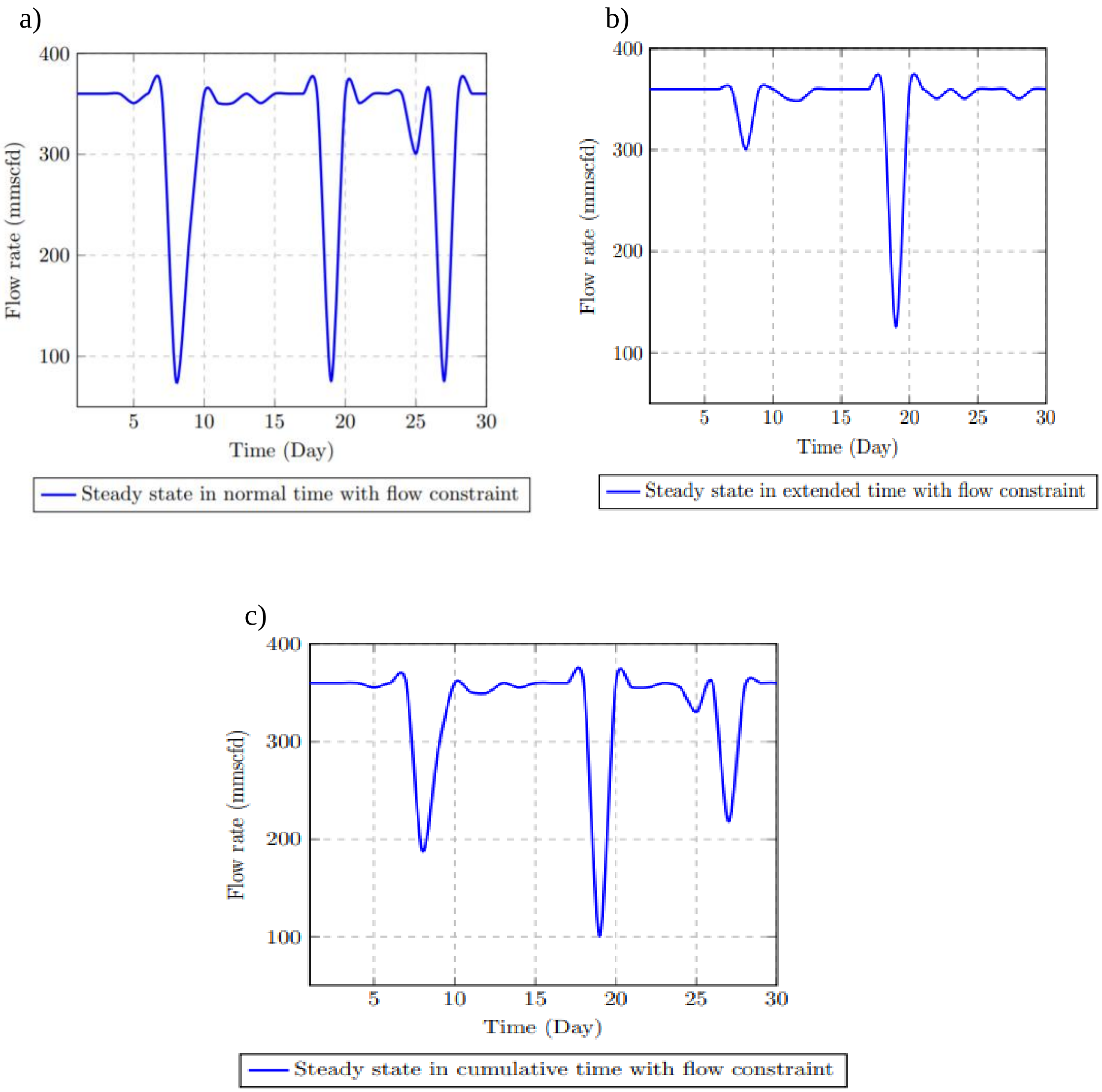


Figure 27: Steady state with flow constraint

The result in Fig. 27 is an indication that the additional operating time of the plant does not affect all the compressors at the same time. The only exceptions are the approved shutdown times of $t8$, $t19$ and $t27$. For the normal period, the no operating time is seen in $t9$ where only $k3$ is affected, while for the extended time, the no operating time is in t8.5 where $k3$ is not operating, and $t19.5$ where $k1, k2$ and $k3$ are not operating. Subsequently, the impact of the plant operating status on the flow rate performance is analysed. Furthermore, overall performance is compared when the flow constraint is removed against overall performance when flow constraint is introduced in the planning horizon.

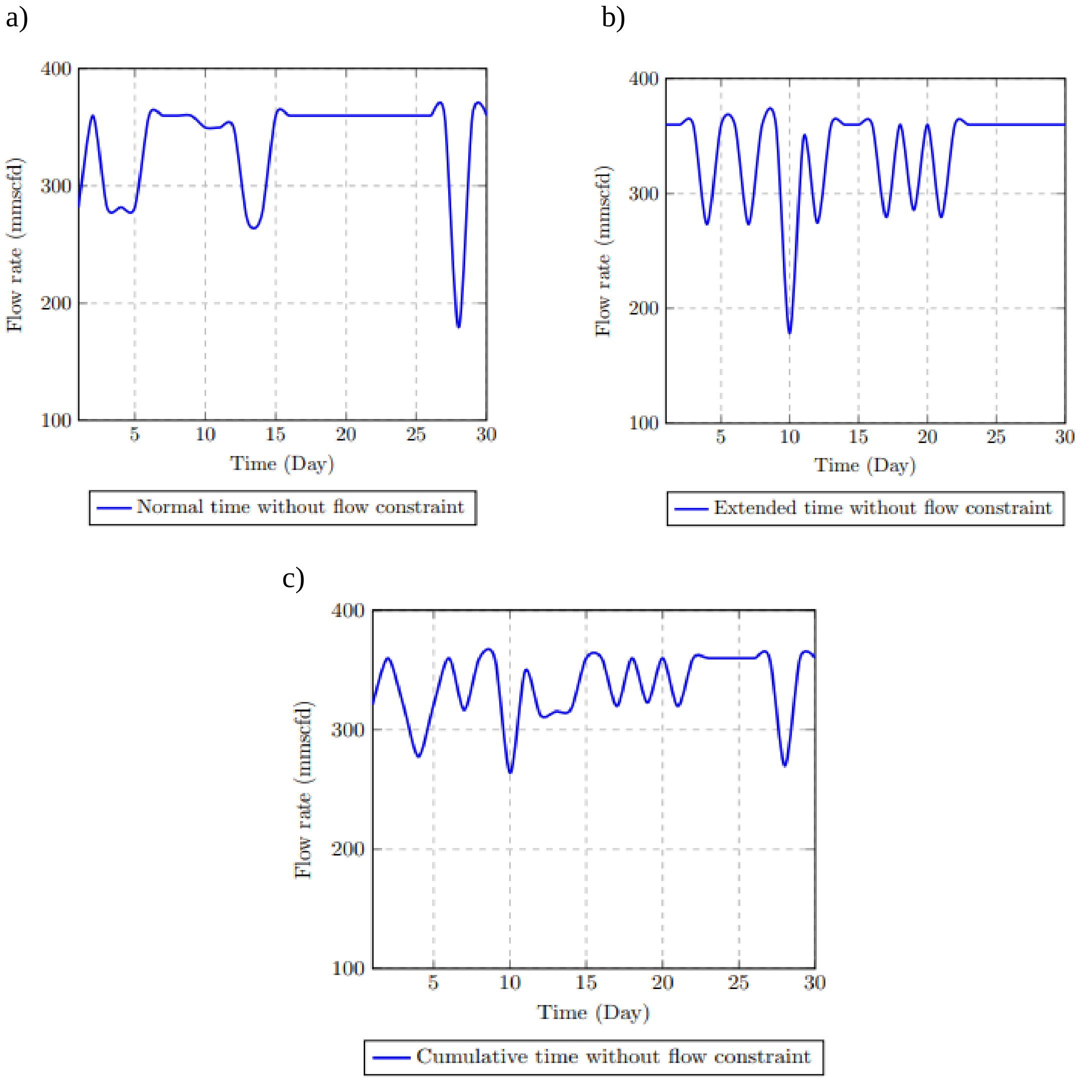


Figure 28: Steady state without flow constraint

Unlike Fig. 27, the extended time series is also introduced without a corresponding upper and lower bound flow constraint shown in Fig. 28 to observe the flow rate performance. In this case, the number of times where at least one to three compressors were not operating increased. However, the defined shutdown times ($t8$, $t19$, and $t27$) performed at optimal because of the additional pathway. The average throughput slightly improved from 336.078 mmscfd when the flow constraint is introduced to 336.900 mmscfd without flow constraint.

5.1.4 Scenario four: Shutdown without redundancy

A worst-case scenario is investigated in addition to the baseline to compare output performances. The idea is to see if optimisation can be obtained without an additional workflow. Therefore, the capacity of node k and node m is set at 250 mmscfd and 360 mmscfd, respectively. From the computation, the analysis obtained shows that the projected shutdown time occurred in each time as input except $t25$, $t29$, and $t30$. Because the supply network is interconnected and the capacity at the compressor determines the supply to node m, monthly loss target L_{kt}^{T} is then introduced and set at 16.490 mmscfd and at least one shutdown is recorded for all shutdown times. Assuming where shutdowns are not expected on all the compressor plants in node k simultaneously within the planning horizon, the following results is obtained as shown in Table 20. An emission loss of 167.31 mmscfd at time t, is initially recorded which is further inputted back as a data parameter for node k.

Table 20: Total supply with no relief pipeline

Consumer	Supply (mmscfd)	Capacity	Demand (mmscfd)	Margin
m	192.670	1000	360	0
n	7.310	N/A	7.310	299.000
q	50.00	N/A	50.00	299.000

The result in Table 20 is the output after running the model. A loss target is introduced in the model and further reduction in throughput is recorded because the shutdown time increased which suggest that an improvement to the system is required which can be achieved using the mitigation planning strategy.

5.1.5 Scenario five: No dedicated storage

The absence of a dedicated storage facility results in a risk of unplanned over-pressuring of natural gas plant nodes. In the event of this, operators vent over pressurised gas for safety reasons. The loss and downtime affect supply to consumers that result in demand and supply disequilibrium. With the introduction of lower and upper bound limits for temporary storage, the demand is fully satisfied on a short-term basis, and output performance increases. However, short-term satisfaction is not sustained for long and, therefore, a limitation. Demand here is satisfied by expansion in capacity and time. Therefore, constraints (11) and (23) can be remodelled respectively:

$$\sum_{j \in J} X^{P}_{(j,k,t)} - Z^{E}_{(t)} \le cp^{\max}_{(k,t)} \qquad \forall_{k \in K, t \in T} \tag{5.1}$$

$$\sum_{j \in J} X^{P}_{(j,k,t)} - Z^{E}_{(t)} = \sum_{k \in K} \sum_{m \in M} Y^{W}_{(k,m,t)} + \sum_{k \in K} \sum_{g \in G} Y^{F}_{(k,g,t)} \qquad \forall_{t \in T} \tag{5.2}$$

At a constant mass flow rate in an extended period time t, the gas supplied from the processing plant to the compressor plant is increased by the additional line packed gas, this is applicable where $\Sigma flow\ in \neq \Sigma flow\ out$.

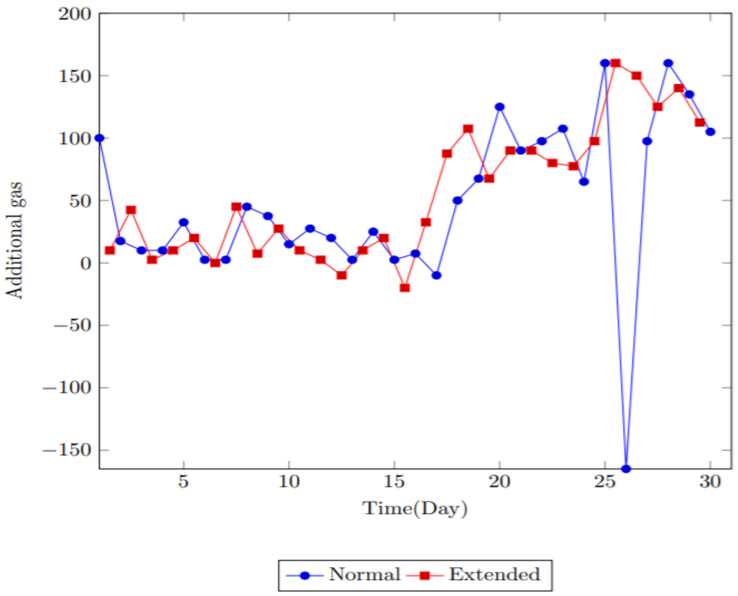


Figure 29: Impact of additional temporary storage

The illustration in Fig. 29, where the impact of the additional temporary storage is displayed, shows the impact of additional temporary storage introduced. The steep drop in storage level in t 26 is caused by downtime effects resulting in no additional storage provision.

5.2 Discussion of results from steady state optimisation

The model developed is run on the GAMS 26.14 software using the CPLEX solver 12 in an intel ® core ™ i7 and a zero-optimality gap within reasonable solution time. The solution for each scenario has an optimal integer output. The result is targeted at optimum performance for the resilience of the natural gas supply chain system. It is shown that, when the plant is fully operational for every time t, at least one plant is supplying gas to consumers based on the contractual agreement. However, this is not always the case, as there are disruptions to network flow recorded. In that instance, the flow changes and the shortages are catered for by introducing redundancy, especially for prolonged shutdowns where temporary storage can only accommodate supply for 24 hours.

The optimisation model is applied to every scenario in the steady state, generating different optimal solutions for each scenario. As already stated, the baseline flow rate is to indicate the initial performance of the supply chain. Improved performance of an additional 127.29 mmscfd is established in scenario two, where $R(k,t)$ = 1 with no pressure drops. Higher improved performance is also obtained in scenario three with mean throughput put at 336.078 mmscfd when the flow constraint is introduced to 336.900 mmscfd when the flow constraint is removed. It shows that when the data point is extended, improved performance is recorded. A worst-case scenario is introduced in scenario four when nothing is done to mitigate the disruption, while scenario five establishes a short-term performance satisfaction caused by temporary storage. During the shutdown period, the volume of loss remained the same at the different mass flow rates, but the shortage varied.

The improved flow is attained if the alternative pathway is operating during the shutdown, while the reduced loss and shortage are recorded if the flow rate for the relief pipeline is less than the flow rate on the mainline. The improved flow means that the mean throughput is increased. If pressure remained the same for all periods, a lower mass flow rate shows a reduction in loss with zero shortage. With the introduction of a lower and upper bound limit for temporary storage, the demand in time t is fully satisfied, and optimality increased. Demand is satisfied by expansion in short time storage, zero shortage, and loss reduction.

On the other hand, if there are no interruptions, shortages and losses are reduced. Overall, because the temperature is isothermal, the relief pipe should be installed between the midstream and downstream, where pressure drop is assumed to be higher under ideal circumstances. The result in Table 16 shows that when the flow constraint is introduced at different mass flow rates, the offline time changes but only increases. The table is summarised as follows:

1. For all possible scenarios, no mass build-up in any node of the network.
2. Each node is constrained to the mass balance law.
3. Best possible scenario with the least offline period is when the mass flow rate is 300/200 psi.
4. The capacity of the initial nodes determines the performance of subsequent nodes. Therefore, the comparison before and after the optimisation, as obtained, shows a reduction in shortages after optimisation, displayed in Fig. 25 and Table 17.

As expected, if the disruption is not exogenous, insufficient supply from initial nodes results in the shutdown of subsequent nodes. To also reduce demand and supply disequilibrium, a lower and upper bound limit for temporary storage is introduced as a new decision to be taken. Further analysis is to estimate the gas in the enclosed pipe during the plant shutdown but within the planning horizon. To determine the amount of gas in the enclosed pipe when the valves at the upstream and downstream end are closed is a way to estimate the gas savings. The length between the two closed valves at the upstream and the downstream end must be known to calculate the gas volume in the enclosed pipeline during the shutdown. For this work, the shutoff valves are estimated within 4 kilometres (km) equivalent of 2.485miles and 13123.4 ft.

1. Pipe diameter 32 inches
2. Gas pressure within the pipe is 1100 psi (same as inlet pressure)
3. Gas temperature is 60°F, equivalent to 15°C

The pipe volume formula is introduced to calculate the volume of the pipe between the inlet and outlet valves, thus:

Pipe volume = π x radius² x length. The radius = inner diameter/2

$$(\mathrm{Pi})\left(\frac{\mathrm{D}^2}{4}\right)(\text{Pipe length in ft})/(144\ \mathrm{in}^2/\mathrm{ft}^2)$$

$$= (3.1416)\left(\frac{1024}{4}\right)(13123.4)\ = 10{,}554{,}489.2006\ \ \mathrm{ft}^2 \qquad (5.3)$$

To calculate in cubic feet:

$$= (10{,}554{,}489.2006\ )/(144) = 73{,}295.063\ \mathrm{ft}^3 \qquad (5.4)$$

Then at atmospheric pressure of 14.696 psi, gas pressure of 1100 psi, the volume of gas is calculated thus:

$$(73{,}295.063\ )(1100/14.696\ )\ =\ 5{,}486{,}157.41\ \mathrm{ft}^3 \qquad (5.5)$$

To convert to mmscfd using $997{,}714.76\ \ \mathrm{ft}^3$/d to 1 MMSCFD at 15°C first °C is converted to °F. Using $(15°\mathrm{C}\ \times\ 9/5\ )$ + 32 = 59°F, which can be approximated to 60°F
Therefore, estimated volume in enclosed pipe = 5.5 mmscfd.

If demand per time t is 360 mmscfd and t = 30 days
Then throughput per day: $360/30$ = 12 mmscfd
Therefore, percentage savings/ volume in enclosed pipe in relation to average throughput = $5.5/12$ = 45.8%

Therefore:
Shutdown time: $12/5.5$ x 24 = 52.36 hrs for the planning horizon. However, in a worst-case scenario if demand per day is 360 mmscfd where t = 1 day, savings on volume in enclosed pipe in relation to throughput = $5.5/360$ = 1.5%
Therefore, enclosed gas in relation to time: $360/5.5$ x $(24/24)$ = 65.45 minutes.

5.3 Conclusion

In this chapter, the developed model is applied in the steady state to optimise resilience and flow flexibility where loss, flow rate, and shutdown effects are considered. It is assumed that the flow is initially in a steady state and is isothermal, with the temperature remaining the same in the node, such that there is no variation in temperature or pressure. The shortcoming of the steady state result is that realistically, pressure and temperature fluctuate because of the closing and opening of the valve when the interruption is introduced, change in atmospheric temperature, and diversion of flow to mitigate the impact.

This proposed mitigation strategy focuses on achieving improved throughput and accounts for emission loss savings regardless of system interruptions. The mathematical model captures the actual performance of an existing network explained in the case study. To have a reduced loss and shortage, the mass flow rate in the relief pipeline is below the mass flow rate in the mainline because the flow rate is a function of both the size of the pipeline and the pressure in the pipeline. The reverse optimisation result indicates that the performance of initial nodes affects the number of shutdowns in the steady state with respect to the applied mass flow rate.

The removal of the lower and upper bound flow constraint and the introduction of extension of the time series indexed data points to ensure that the time sequence has successively equally spaced points and zero variation with respect to time produced an optimum value. The optimal value obtained is that free flow from the relief pipeline into the sale line is expected. The optimisation also shows that by maintaining the capacity of initial nodes at a certain level, the continuous functionality of the supply chain can be attained. Also, to increase emission loss savings, operators should ensure minimal shutdowns of plant nodes, while the need for an alternative pathway as a redundancy backup strategy will go a long way to increase supply and environmental gains to operators.

Chapter 6

Transient Analysis During Shutdown

6.1 Transient flow due to plant shutdown

This chapter is introduced to process the behaviour of the plant node over time, given certain circumstances. The steady state analyses the flow when the plant disruption and subsequent shutdown is introduced, such that pressure and temperature profile were constant, and the transmission flow rates were steady through the planning horizon. In contrast, pressure variation is a significant feature under the transient condition, and the system is dependent on time in the dynamic state. Although the transient simulation is detailed and realistic of the process behaviour over the planning horizon, it may lead to wrong conclusions and be subjective. The transient state can be complicated; simplifying the process by running the mathematical simulation using time series to arrive at significant results is ideal. The decision on the time granularity is in congruence with the purpose of the model.

The investigation is conducted when the compressor plant is shutdown resulting in valve closure on the mainline pipeline in the transient state. This variation is determined and analysed for the mainline and the relief pipeline. The transient effects of time-varying consumer demand for natural gas affect the compressor and pipeline operations mainly just ahead of the delivery point. Studying the transient condition is restricted to the mainline transmission node with an extended observation time until the opening of the relief valve. The impact on the flow rate is compared with the steady state condition. The transient state for optimisation is usually time-dependent, and therefore the introduction of a time-bound is required. The simulation model in a transient state is more detailed and realistic as it replicates the actual behaviour of the process over time [139]. The time series introduced is to study the behaviour pattern of the process. As such, there is a derivative with respect to time, pressure, and temperature. The expectation is that no additional pressure is being generated; this illustrates the transient condition during the plant shutdown. The expectation of the transient behaviour investigated from 06:00 hrs day 1 to 06:00 hrs day 2 is that the unsteady pressure in the pipeline will affect the flow rate in the mainline and the relief pipeline. For further explanation, refer to subsections 6.1.2 and 6.1.3.

6.1.1 Scenario one: Variation in pressure and mass flow rate

In this scenario, the change from a steady to a transient state when shutdown $R(k,t)$ = 1 is examined. The change may refer to a variation in pressure and mass flow rate. This scenario illustrates the action taken when the compressor plant is shutdown, and there is no further pumping of gas from the upstream, triggering the closure of the valves at the start and the end nodes on the mainline pipe and compressor station. The valves at the start and end of the mainline pipeline and compressor station are known as the inlet and outlet nodes valves. The outlet valve could also represent the valve between the mainline pipeline and the relief pipeline. During the disruption and subsequent shutdown, the trapped gas undergoes pressure variation, which stabilises over time due to friction and loss of inertia, resulting from the gas velocity reduction, as explained in Menon [68].

The pressure surge caused by the variation, as explained above, is reduced as the outlet valve leading to the alternative pathway is opened. However, the expectation is that the pressure surge will be within the upper bound limit of the maximum pressure. It is assumed that the delivery pressure is within the acceptable limit, and as such, no penalty cost for deviation. Figs. 30 and 31 present the rate of pressure variation in the mainline pipeline. The operating status of the plant node between the gas plant and the compressor is multiplied by the binary variable for operation on lower and upper bounds of the flow to determine the variation. As stated earlier in 6.1.1, the studied pressure variation in time series is for a defined period with a cumulative period of 24 hrs. Each hour is examined at every 6 mins interval making a total of 10 points for every hour.

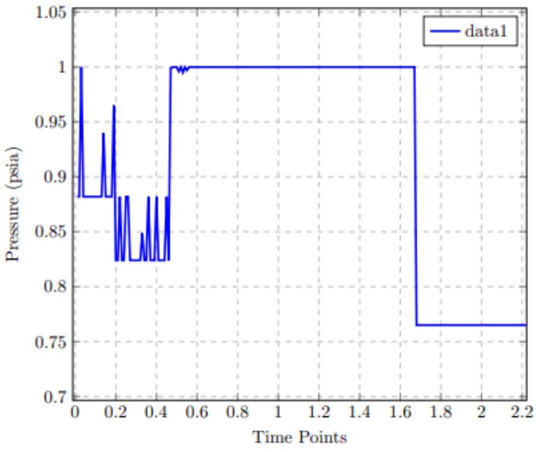


Figure 30: Mainline pressure variation time series at maximum mass flow rate

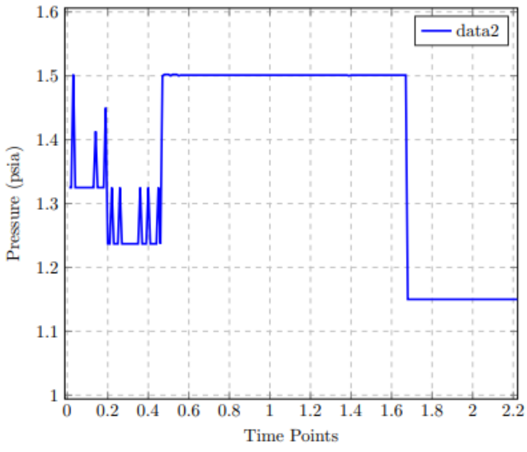


Figure 31: Mainline pressure variation time series at minimum mass flow rate

The time series of the pressure in the mainline for both Figs. 30 and 31 surge to maximum pressure during shutdown between points 0.48 to 1.67 at approximately 13:50 hrs. The pressure then drops to a stable rate of 0.765 and 1.15, respectively, from point 1.68 to 2.22 at approximately 10:00hrs. The illustration in Fig. 32 further explains the pressure behaviour when $R(k,t)$ =1. At flow rate (s_1), all line compressors in the compressor station meet the mainline (w, x) at point OP_1. When the compressor station is closed, the gas finds its way to the relief pipeline (y, z), and because there is already pressure built up between the two closed valves in the mainline, the new operating point (OP_2) is at a reduced flow rate (s_2). The control valve on the relief pipeline controls the flow of the gas supplied from the mainline.

Furthermore, if a new compressor is installed in the relief pipeline to increase delivery pressure, the new operating point will be at OP_3 where the gas flow rate is (s_3). The shift in the operating point from OP_1 to OP_2 and then to OP_3 shows the shutdown effect and the introduction of the additional pathway. When the relief pipeline is fully in operation, it is assumed to substitute for the shutdown period, such that $R(k,t)$ =0. The loss at this point is negligible because the trapped gas is routed through the relief channel.

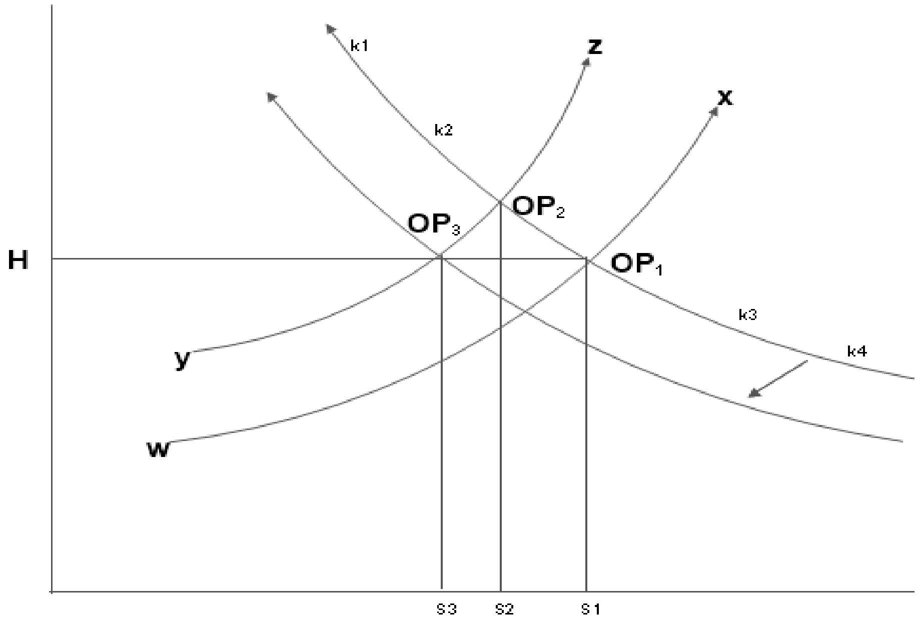


Figure 32: Unsteady movement due to compressor station shutdown

Table 21: Operating status of compressor plant just before and after shutdown

Extended Time (t)	$k1$	$k2$	$k3$	$k4$
7.5	1	1	1	1
18.5	1	1	1	1
26.5	1	1	1	1
27.5	0	0	0	1
28	0	0	1	1
28.5	1	0	1	1
29	1	0	1	1
29.5	1	1	1	1
30	1	1	1	1

In the extended time, the operating status of the compressor in Table 21 indicates when the compressor is operating just before shutdown and the startup. The table suggests that only $k4$ is operating just before and after the shutdown time for all the shutdown time points in the planning horizon. The indication is that gas can bypass $k1, k2, and\ k3$ through to $k4$ before and after shutdown. With the introduced extended time series, the sequencing of data points is indexed and equally spaced.

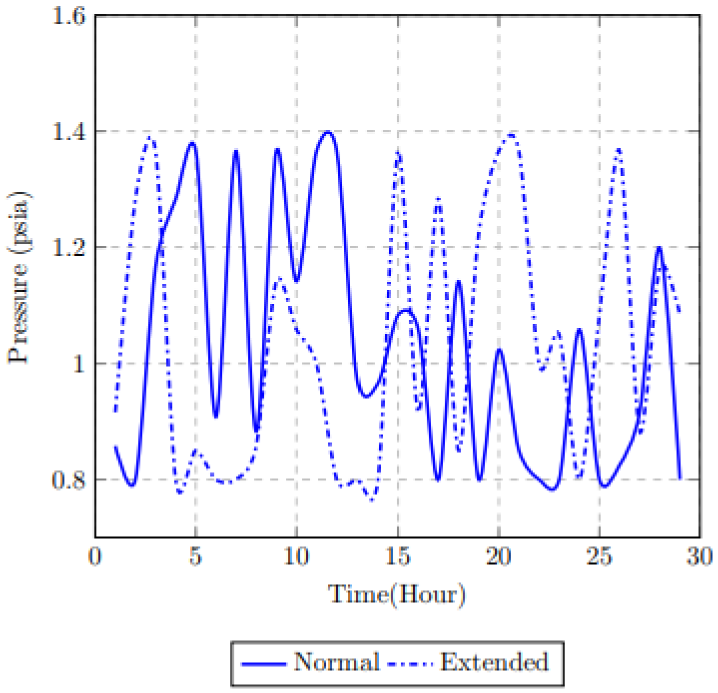


Figure 33: Interaction of outlet pressure at the point of variation where z equals 1

The pressure interaction in the outlet node is determined by multiplying the binary by the upper and lower bound of the disruption in the compressor node. Ignoring the bound limit of the inlet and outlet pressure while introducing the flow rate for the relief pipeline, the time series at the point of variation is then split to observe the pressure interaction, as seen in Fig. 33. In the mentioned figure, there is better interaction between the pressure variation in the normal and extended time as displayed where the compressibility factor equals 1 ($z = 1$). Although there is a mixture of gas from different sources, the deviation of the real gas from the ideal gas is insignificant and therefore does not affect the throughput in the relief pipeline.

Assuming the compressibility factor is less than 1 ($z < 1$), the variation in the relief pipeline is then shown in Figs. 34 and 35. A reduced mass flow rate from 400 mmscfd in the mainline to 120 mmscfd in the relief pipeline during the mainline shutdown without changing the originating pressure will cause a pressure rise, which will be compensated as the gas enters the sale line. At this point, the relief pipeline and the sale line are operating simultaneously.

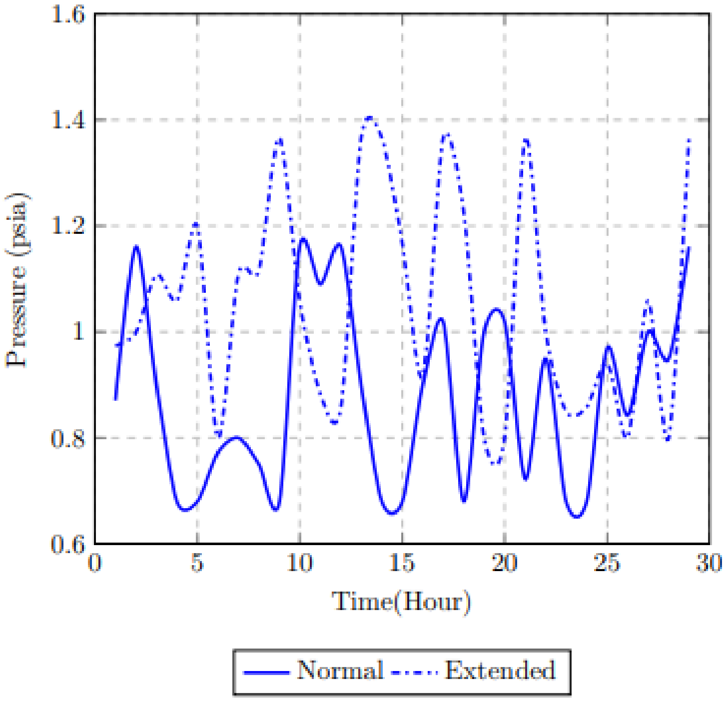


Figure 34: Interaction of outlet pressure with lower compressibility factor where z is less than 1

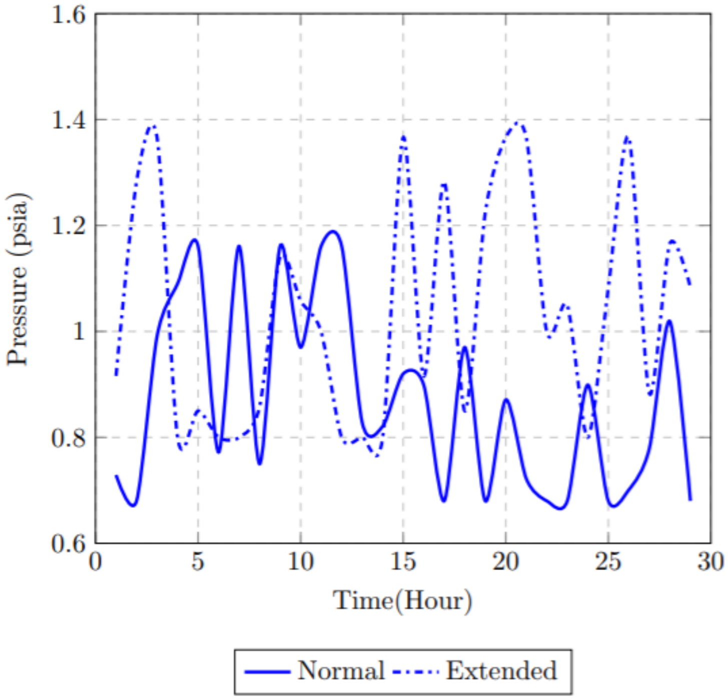


Figure 35: Interaction of outlet pressure lower than mainline pressure with a lower compressibility where factor z is less than 1

If a compressor is installed in the sale line, the delivery pressure increases if the discharge pressure remains the same. However, to maintain the pressure within the limit bound, the inlet pressure into the relief pipeline is then multiplied by a pressure coefficient. When the lower and upper bound limits are introduced, then the pressure in the relief pipeline is controlled within the limit. The effect of this mitigation strategy is investigated when the time series of the pressure-flow at the optimised level for the mainline is compared with the time series of the pressure-flow when the initial node valve is opened during the compressor plant shutdown period as shown in Figs. 37 and 38.

Time Transient:
Number of compressors: 4 compressors x 60 = 240mins
Number of points per hour = 10
To get the number of hours in a day: 240mins/10 = 24hrs
To determine the minutes per interval: 60mins/10 = 6 minutes per time interval

6.1.2 Scenario two: Transient caused by inlet and outlet nodes closure

Scenario two explains the transient condition caused by the interruption, which leads to a closure of the inlet and outlet nodes in the mainline. The mainline closure during the disruption produces an expected pressure build-up. This gas accumulation suggests that an expected pressure rise with time after the closure at these nodes. The gas compressibility allows for continuous pumping of gas from the upstream over a period, which eventually increases the line pack in the midstream and downstream. This activity of pressure build-up can happen without the operator's knowledge. However, if the closure of the nodes is within an allowable time, the gas can continue to flow from the upstream, which is line packed until the inlet and outlet nodes are opened. The challenge becomes evident when the problem on the disrupted node is not fixed within the allowable time so that the valves are shut continuously beyond the projected allowable time.

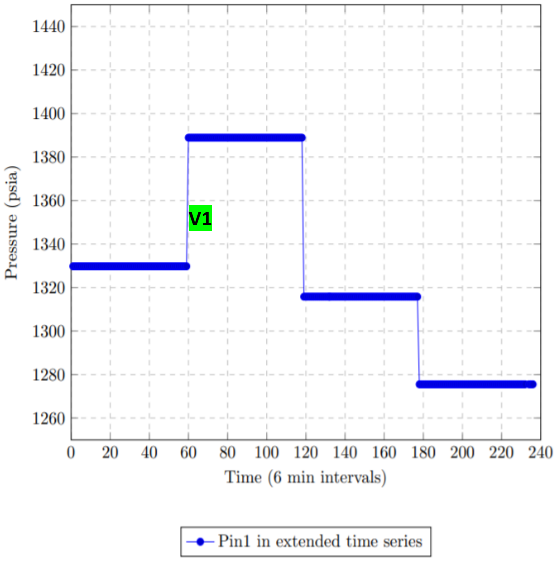


Figure 36: Mainline pipe node at optimised level

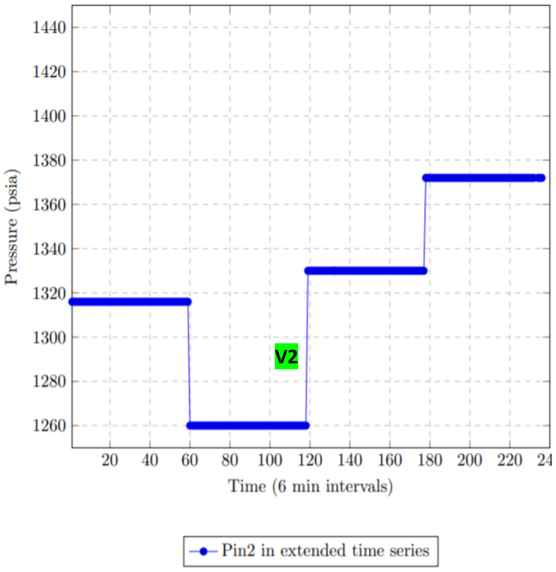


Figure 37: Pressure when relief valve node is opened

The diagrams in Figs. 36 to 38 displays the mainline pressure behaviour during disruption analysed over 24 hrs period at 6mins intervals. In Fig. 36, inlet pressure begins to increase at approximately 11:56 hrs causing the outlet pressure to decrease once the relief valve is opened, as shown in Fig. 37. When the control valve in the relief pipeline is opened, the outlet pressure is relatively stable but changes slightly over time, and as gas continues to enter the relief pipeline, the variation becomes more evident over time, as seen in Figs. 38 and 39 and then stabilise afterwards as it begins to feed into the sale line. Assuming the mainline inlet valve is re-opened, as shown in Fig. 38, pressure begins to increase at approximately 17:48 hrs, which is offset as the gas begins to flow into the relief line.

The essence of this mitigation is to reduce the possible impact on the system when the disruption goes beyond the allowable time. This mitigation also minimises the interruption effect on the system operators and consumers. A known strategy is the deployment of backup storage to reduce the effect of a prolonged shutdown; however, storage capacity is limited and can only feed the sale line for a defined period.

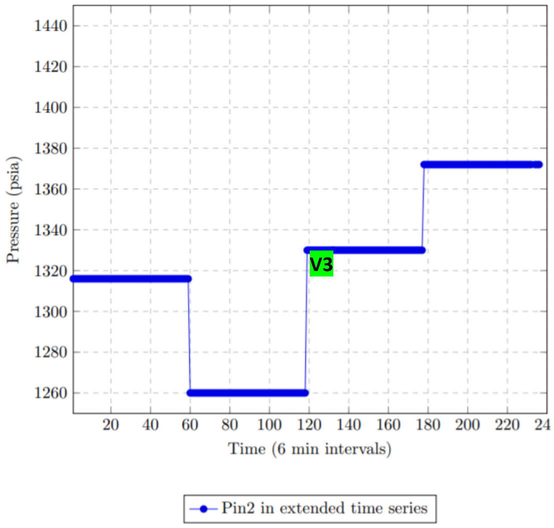


Figure 38: Pressure when mainline valve node valve is re-opened

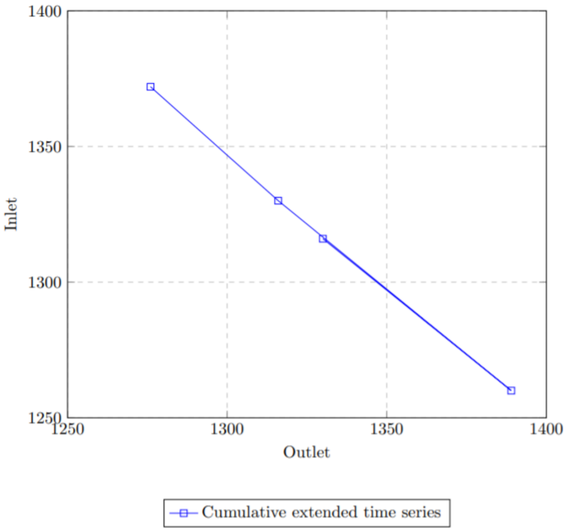


Figure 39: Extended times series optimised level of pressure

If the intention is to increase the flow rate using the capacity for expansion, the increased capacity will cause a pressure drop if the originating pressure remains the same. The pressure drop means a loss in throughput efficiency; therefore, it is mitigated with the relief pipeline introduction. The opening of the relief pipeline will help maintain the right delivery pressure at the sale line. The discharge pressure at the upstream cannot be adjusted to make up for the drop. The reason is that the inlet valve has been closed due to the shutdown of the plant node. A reference point for discussion is in [68], where the author suggests that the average gas pressure should be kept as high as possible to achieve adequate gas pipeline transportation.

The interaction of the extended time series for pressure at the mainline is shown in Fig. 39. The extended time series accounts for data points that may have variations that would ordinarily have been ignored. Further explanation is presented in Table 22. These performances are influenced by the individual bound limits introduced such that only one upper and lower bound is introduced simultaneously. The improved flow rate is fully optimised when the gas flow from the mainline to the relief pipeline is operating and when the valve from the mainline to the relief pipeline is opened.

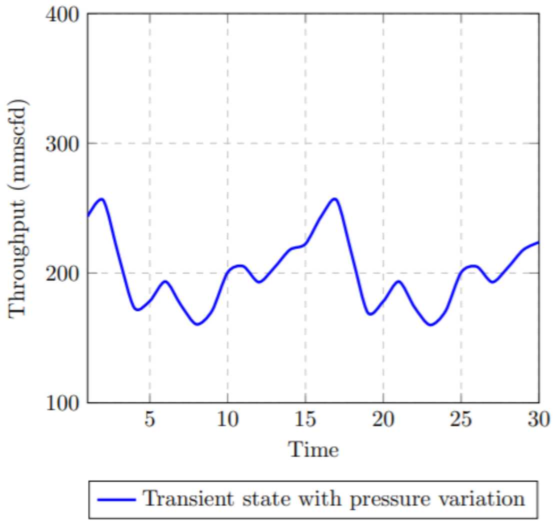


Figure 40: Throughput with pressure variation in extended time

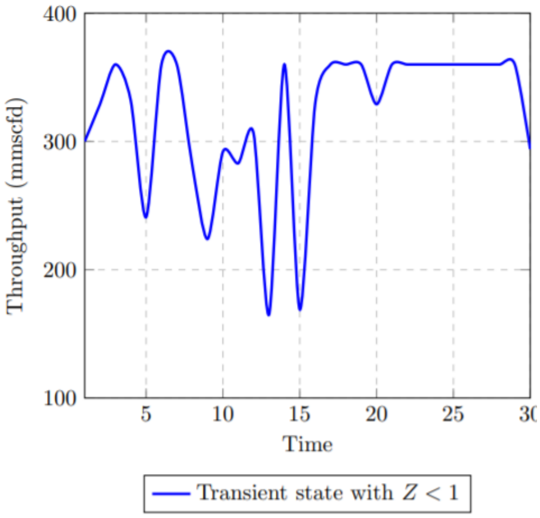


Figure 41: Throughput within pressure bound limits, lower compressibility factor

The output in Figs. 40 and 41 are both obtained in extended time. The impact of the pressure change on the average throughput in Fig. 40 shows that the flow rate dropped to 200.38 mmscfd compared to the flow rates in the steady state, however, an improved flow rate is displayed in Fig. 41 when pressure bound limit is introduced.

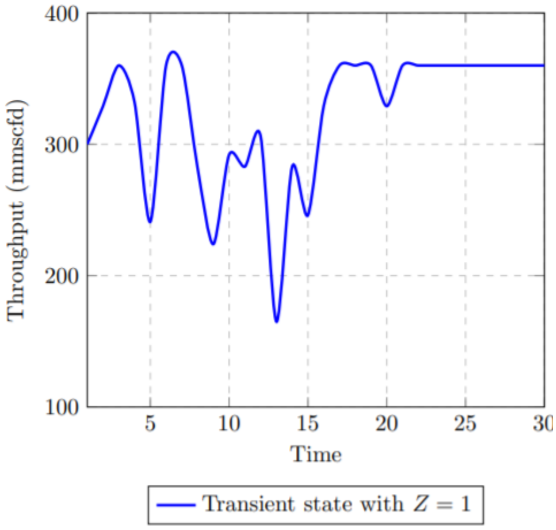


Figure 42: Throughput within pressure bound limit in extended time

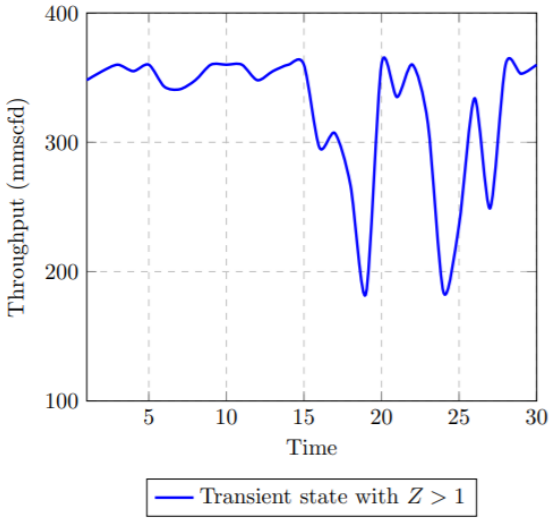


Figure 43: Throughput within pressure bound limits, higher compressibility factor in extended time

A close investigation indicates that the flow rate shown in Fig. 41 can be further optimised and is best firstly, when the relief pipeline is introduced, and secondly, when the compression factor equals 1 with extended time, as displayed in Fig. 42. The indication is that the effect of the shutdown is fully minimised. An optimised throughput is obtained, as shown in Fig. 42, when the pressure bound limit is introduced and when the compression factor is equal to 1. Although the average throughout is given as 321.17 (mmscfd), which is an improved flow rate, the average optimised throughput in Fig 43 is given as 327.03 (mmscfd), and this is obtained when the compression factor is greater than 1.

These results are obtained during pressure variation and in extended time in the mainline. The transient state is expressed as $\Delta P/\Delta T$ such that the pressure change is subject to the change in time, where:

pressure variation = $\Delta P = (\Delta P = P_1^2 - P_2^2)$

Time variation = $\Delta P = (T_2 - T_1)$

In studying the transient behaviour, operators will ensure that the pressure is within the required limit.

Table 22: Mainline disruption

Description	Performance	Pressure	Behaviour
Mainline pipe node when the valve is closed at inlet node.	Increased at 11:54 Decreased at 17:48 Decreased at 23:42	1389 1316 1276	Stable Stable Stable
Opening of the relief valve and re-opening of mainline valve.	Decreased at 11:54 Increased at 17:48 Increased at 23:42	1260 1330 1375	Stable Stable Stable

6.2 Discussion of results from transient state optimisation

This chapter investigates the transient pressure analysis in the mainline and the relief pipeline due to the disruption and mitigation strategy to determine the mean flow rate. The pressure variation under the transient condition is determined with a defined granularity of time series in an accumulative period of 24 hrs. This unsteady flow condition is restricted to the mainstream transmission node when the disruption occurs and the alternative pathway when the relief node is opened. The relief pipeline helps to achieve a pressure drop and increases the flow rate. If the temperature is isothermal, the relief pipeline can be installed downstream of the transmission echelon because the pressure drop at that point is higher. The result shows that using a higher compressibility factor when pressure bound limit is introduced produces a higher flow rate. The impact on the flow rate or throughput performance is compared with the steady state condition obtained. Finally, an understanding of the possible nodes highly susceptible to disruption is essential in planning for the alternative pathway in the supply chain network.

The transient state has been introduced in this chapter to demonstrate the behavioural pattern of the disrupted plant. Critical in this chapter is to understand the reaction in the affected nodes as a result of changes in the natural gas pressure. The findings indicate that as the downstream pressure is reduced, keeping the upstream pressure constant, the flow rate will increase. As shown in this chapter, the additional pathway can remain open even after the mainline valves are re-opened, providing a two-way simultaneous flow to compensate for shortages pending when supply is improved. The three critical nodes identified as pivotal includes the gas plant, the compressor on the mainline, and the relief pipeline. These results are generated within a defined time. When considering an extensive system with a network of interconnected nodes, changing the pressure or composition in one part of the network could influence capacities and flow rates in the other nodes; therefore, taking a system perspective of the decision processes is essential. The alternative pathway shows a reduction in pressure drop and an increase in flow rate. The table below compares the baseline flow rate to the optimised solution in different scenarios in both steady and transient states.

To validate the steady state, the best optimal result in comparison to alternatives is compared among all feasible alternatives. In Table 23, the results from all scenarios in both steady and transient states are presented. The best optimised solution is found in the steady state when the flow constraint is removed.

Table 23: Comparison of throughput across different cases

State	Description	Throughput (mmscfd)
Steady	Optimised flow obtained if the capacity of plant k is the same for all period in the planning horizon.	327.67
	Optimised flow is obtained if the capacity of plant k varies at different rates in the planning horizon.	276.38
	Optimised flow is obtained when the flow constraint is introduced.	336.078
	Optimised flow is obtained when the flow constraint is removed.	336.90
Transient	Pressure variation in extended time.	200.38
	When compression factor equals 1 with an extended time.	321.17
	When pressure bound limit is introduced in extended time.	323.37
	The compression factor is increased in extended time.	327.03

6.3 Conclusion

Chapter six has shown that the values that characterise the natural gas flow in the system in the transient state are dependent on time. Establishing the time variable introduces a new dimension to the mathematical model. The model applied in the transient state identifies the flow rate pattern resulting from pressure variation in the enclosed section. The pressure interaction is studied closely to analyse the disruption impact in the mainline section that leads to the alternative pathway by introducing the binary and upper and lower bound of the disrupted section within the planning horizon. For the analysis of transient flow, pressure variations are investigated, although the temperature remains isothermal. Due to the potential broad variety of transient behaviours displayed by the transportation process in the transmission echelon of the supply chain, the applied model obtains real values for performance evaluation of the process. Although transient analysis is argued to be harder to solve from the optimisation perspective, the analysis corroborates an improvement in the throughput through system optimisation.

Chapter 7

Benefits of Resilience of the Natural Gas Supply Chain

7.1 CO_2-equivalent on methane savings

This chapter does not entail a life cycle assessment of the gas network, which requires evaluating the environmental impact of a wide range of the system components through their entire life cycles [140]. However, part of the study has established the estimated amount of trapped gas between the inlet and outlet closed valves during the shutdown. To determine the emission resulting from the gas loss during shutdown on a network node, firstly, reference is made to the amount of gas calculated in the enclosed pipeline. The conversion of 1 mmscfd of gas at 15°C, equivalent to 60°F at isothermal condition, equals 847210.92kg/hr in flow rate. Considering the above explanation and based on this operating condition, the amount of CH_4 emanating from the gas loss before the optimisation is 9,981.97 million kg/hr, while the CH_4 after the optimisation is 144.95 million kg/hr. The result showed a significant reduction in CH_4 after optimisation. The savings on shrinkage cost from loss reduction is shown in Table 24.

Table 24: Shrinkage cost before and after expansion

Shrinkage cost (Loss)	Volume of loss (MMSCFD)	US$3 per MMBtu (converted to MMSCFD)	US$5per MMBtu (converted to MMSCFD)	US$7 per MMBtu (converted to MMSCFD)
Before optimisation	11,782.15	36,760,308.00	61,267,180.00	85,774,052.00
After optimisation	171.09	533,800.80	889,668.00	1,245,535.20

Potency:

As already established in chapter one, methane (CH_4) as a greenhouse gas is several times more potent than CO_2, absorbing about 25 times more energy than CO_2 over a century; it contributes to global warming by slowing the rate of electromagnetic radiation. The potency of the trapped gas is calculated in terms of CO_2 equivalent. If 1kg of methane is considered 25 times more potent radiatively than CO_2 on a 100-year interval Global Warming Potential as stated in Gao and You [29], then 25kg of CO_2 will be equivalent to 1kg of methane. Consequently, to determine the savings on CO_2-eq, methane is first converted to kg/hr. The gas loss before the optimisation is given as 9,981.97 million kg/hr, loss savings is calculated as:

$$9{,}981.97\ \text{million kg/hr} - 144.95\ \text{million kg/hr} = 9{,}837.02\ \text{million kg/hr}$$

$$1\text{x} - \text{carbon dioxide } (\text{CO}_2) = 25\text{x} - \text{methane } (\text{CH}_4)$$

$$\text{i.e emission 1kg of CH}_4 \text{ savings is equivalent to 25kg of CO}_2$$

$$9{,}837.02\ \text{million kg x } 25 = 245{,}925.5\ \text{million kg of CO}_2\text{eq} = 245{,}925.500\ \text{tons of CO}_2\ \text{equivalent where 1 ton} = 1000\text{kg.}$$

Alternatively, using the carbon equivalent estimation provided in Shahpari, Aminsharei, and Ghashang [141], converting the loss savings of 9,837.02 million kg/hr to tons = 9, 837.02 tons of methane gas. Therefore, it has a global warming potential of 245, 925.500 tons of CO_2-equivalent.

Supply chain performance:

The determine the supply chain performance, the calculation is given as:

$$1 - \frac{\text{total shutdown period in the planning horizon}}{\text{total time in the planning horizon}}$$

Total maximum operating hours for the entire planning horizon excluding planned shutdowns is given as: 36 x 30 x 24 = 25,920 hours. As already established in chapter five, three unplanned shutdowns in the planning horizon are represented as $t8, t9, and\ t27$. If t = 30 days, then total unplanned shutdown time is given as: 3 x 30 x 24 = 2,160 hours

Supply chain performance = 90.9%

7.2 Sensitivity analysis

For the needs of this study, the sensitivity analysis is conducted on three parameters by observing the changes in the objective function in relation to changes in the parameters of the model. This means that the sensitivity analysis is conducted on the relationship between the mass flow rates, pressure, and the optimality value. The degree of satisfying optimum result increases at a higher pressure and lower mass flow rate. If maximum pressure remains the same for all periods, a higher mass flow rate and a lower outlet pressure will result in a lower optimum value. The relationship in Table 25 is shown in Fig. 44.

Table 25: Output performance

Scenario: $Z^{A}_{ijt} = X^{P}_{jkt}$	Mass flow rate	Optimum value when pressure is highest	Optimum value When pressure is medium	Optimum value When pressure is lowest
X^{P}_{jkt} =1040	380/200	8.34 E+7	7.10 E+7	6.49 E+7
X^{P}_{jkt} =1040	360/200	8.40 E+7	7.16 E+7	6.54 E+7
X^{P}_{jkt} =1040	340/200	8.45 E+7	7.27 E+7	6.63 E+7
X^{P}_{jkt} =1040	320/200	8.51 E+7	7.36 E+7	6.70 E+7
X^{P}_{jkt} =1040	300/200	8.56 E+7	7.54 E+7	6.85 E+7

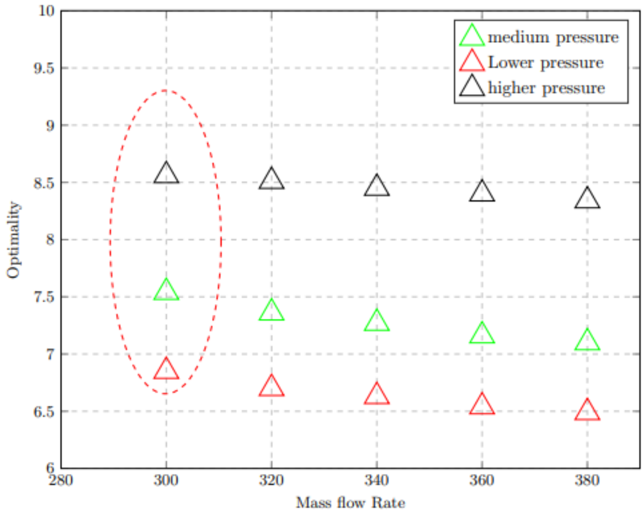


Figure 44: Pressure effect and mass flow rate on optimality value

7.3 Conclusion

In this chapter, the CO_2-eq savings from the optimisation is calculated. The CO_2-eq on the gas loss savings and the sensitivity analysis conducted on key parameters are two areas addressed in chapter eight. The sensitivity analysis demonstrates the effect of changes in parameters on optimal system throughput. In this chapter, the associated gas loss reduction effect is analysed relating to the CO_2 equivalent. Increasing efficiency is an essential measure for reducing environmental impact, including carbon dioxide emissions, a primary greenhouse gas. As established already, the dry gas is 100 percent methane, meaning that the savings in emission loss are methane; therefore, in this chapter, the equivalent savings of methane emission is converted to CO_2. The CO_2-eq is a measure of how much the savings on emission loss in the planning horizon would have contributed to global warming, relative to carbon dioxide. Two different methods were used for the calculation based on the optimal result. As stated already in chapter one, the annual CO_2 equivalent into the atmosphere is 16million tons. Therefore, compared with total annual emission in the country of study, a total of 1.23 percent low to 1.54 percent high annual cut of CO_2 equivalent from the supply chain optimised is achieved over the planning horizon.

Based on the calculated loss savings, a net loss methane savings is calculated as 11,611.06 mmscfd, equivalent to 9,837.02 million kg/hr and $36,266,5507.2 value using a conservative wholesale gas pricing. It is noteworthy that confronting the enormous environmental challenge of present-day reality and the need to control the continuous release of CO_2 into the atmosphere from the gas network is the driving force for this section of the work. Finally, the sensitivity analysis shows the relationship between a pressure range of 1000 to1400 psi and a mass flow rate of 300 to 380 mmscfd on the optimality value. This is obtained in a steady state where $Z_{ijt}^{A} = X_{jkt}^{P}$.

Chapter 8

Economic Analysis for the Alternative Pathway

8.1 Cost estimation

Following the modelling of the optimisation problem and the results presented in chapters four, five, and six, this chapter provides a comprehensive and structured approach to estimate the proposed alternative pathway's economic feasibility through cost estimation. The cost analysis method adopted in this chapter involves the definition of the system's key cost components, as follows: 1) Capital Expenditure (CAPEX) where, the relief pipeline size, length, material, and labour, cost overrun, and inflation are key parameters, 2) Operating Expenditure (OPEX), including the administration cost, environmental permit, maintenance, and labour cost, 3) Abandonment Expenditure (ABEX) estimation, which involves costs associated with the decommissioning of the project during the expiration of the life span of the asset, as well as the, 4) Financial Expenditure (FINEX) involving the costs of obtaining capital, the weighted average cost of capital (WACC), inflation, and net present value (NPV).

The various capital cost components for a typical gas pipeline system are reviewed along with the recurring annual costs, such as operation and maintenance, fuel, and administrative costs. The cost analysis is carried out to identify any trade-offs between cost and loss savings. For broader cost analysis, the domestic price estimate is compared with the regional price estimate. The cost estimates are then benchmarked across industry and global peer projects. Also, for the material input, two different pricing is often adopted for export and domestic price. There is a challenge with executing a controlled pricing regime in the domestic market; however, this is not the same for gas export market price. In general, natural gas price is not fixed and varies from region to region and throughout time [30]. The domestic market price adopts the export parity netback gas price (EPP) or the wholesale prices based on the pricing mechanism. The price provided by the wholesale gas price survey 2018 [142] puts it according to regions per MMBtu, where 1040 MMbtu = 1 MMscfd. See Table 26.

Table 26: Regional wholesale gas pricing [142]

Regional	Africa	Asia	Asia Pacific	Europe	FSU	Latin America	Middle East	North America
US$ per MMBTU	3	6.1	7	6.1	1.9	2.8	2.1	2.9

A major challenge is that domestic gas price has historically been far lower than export price, putting it at about US$ 0.5 -US$ 2.5/MMBtu for lower and upper limits. For clarity, it is assumed that 1 Mscf = 1 MMbtu. The case study puts the domestic price at US$ 3.3/Mscf, where 1000 Mscf = 1 MMscfd. However, it is only realistic that the domestic gas price should not be below the minimum wholesale gas price to cover production costs.

8.1.1 Capital expenditure (CAPEX)

In this subsection, three different CAPEX estimates for natural gas pipelines are used as this will enable a detailed analysis of the capital cost to be incurred. The cost estimates include the World Bank midstream infrastructure cost estimate, projected domestic cost estimate, and regional reference cost estimates. The CAPEX is calculated first as an independent cost to a proposed new mainline gas transportation link as option A. For the second option, the CAPEX is calculated as a retrofit cost to an existing mainline gas transportation infrastructure as option B. The cost of installing this alternative pathway is measured against the proposed length of the pipeline. The cost for compressors is ignored and will only be introduced once the length of the pipeline ≥ 80 km. Labour and material usually take the chunk of the expenditure. Furthermore, in Table 27, below are the parameters for project option A and option B, respectively, and the reference cost estimates. These parameter estimates are used to calculate the net present value of the project options. The CAPEX's components include material, labour, terrain, and miscellaneous with the addition of incremental labour, tariff, environmental permit, cost overrun, and inflation for an existing project in option B, as shown in Figs. 45 and 46. For a further breakdown of the cost composition using the two project options, see Appendix 6.

There are generally no approved cost for pipeline infrastructure due to the complexity of terrain and policies adopted. For countries in the Sub-Saharan region in Africa, few long-distance pipelines are available to determine a robust pipeline capital cost benchmark [143]. A reliable reference point for this work is the World Bank report [143] that adopted a capital cost index provided in Kevin, Julio, and Andrew [144] for midstream infrastructure through 2035. For most of the work, the reference cost index in Kevin, Julio, and Andrew [144] is adopted. As provided for 2019, the CAPEX is US$ 63,041 per inch-mile for both options pipeline infrastructure projects is consistent with inflation-adjusted cost data. This is a rule-of-thumb for capital cost index.

Table 27: Techno-economic parameters for both project options

Parameter	Unit of Measurement	(proposed project-option A)	(existing project - option B)
Pipeline length	Km	32	32
Number of relief pipelines	Qty	1	1
Project life	Year	30	30
WACC	%	9.67	10.48
CAPEX	US$/mmscfd	15,041,990.08	22,809,585.57
OPEX	US$/mmscfd	8,790,550.00	5,389,645.01
Decommission	US$/mmscfd	8,790,550	8,790,550
LCOE	US$/mmscfd	1.631930768	2.646590895
Corporate tax	%	30	20
Gas price	US$/mmscfd	3.3	3.3

Option A: Independent cost to proposed transportation infrastructure (proposed project)

For option A, this additional pathway's network infrastructure refers to a proposed or new project with a conservative life span of 30 years. The CAPEX of seven different sizes of the projects and the variation in the component costs for each pipeline size is shown in appendix 8. If the regional and domestic cost estimates provided in Table 27 above is used, the value of a proposed mainline pipeline can be calculated. The CAPEX for the additional pathway line, therefore, is calculated as:

$$\mathrm{KP_{ip}} = \frac{\Delta\mathrm{KX}\left(\frac{\mathrm{ip}^{\mathrm{n}}}{\mathrm{n}}\right)}{\mathrm{U_p}}\ \mathrm{P_z}$$

where:

$\mathrm{KP_{iP}}$ = unit capital cost of relief pipeline

$\Delta\mathrm{KX}^{\mathrm{ip}}$ = total capital cost of new project per km

n = length of pipeline in km

$\mathrm{P_z}$ = size of relief pipeline

$\mathrm{U^p}$ = size of the new project pipeline

The formula above is a function of the total capital expenditure of the pipeline infrastructure project represented as KP_{iP}. The size and length of the relief pipeline are calculated based on the CAPEX of the pipeline project. If 1 km @ 48 inches = US$ 3,149,224.81 (upper limit), then:

$$1\text{ km @12 inch} = \frac{3{,}149{,}224.81 \times 12}{48} = \text{US\$}787{,}306.20 \text{ (no compression)}$$

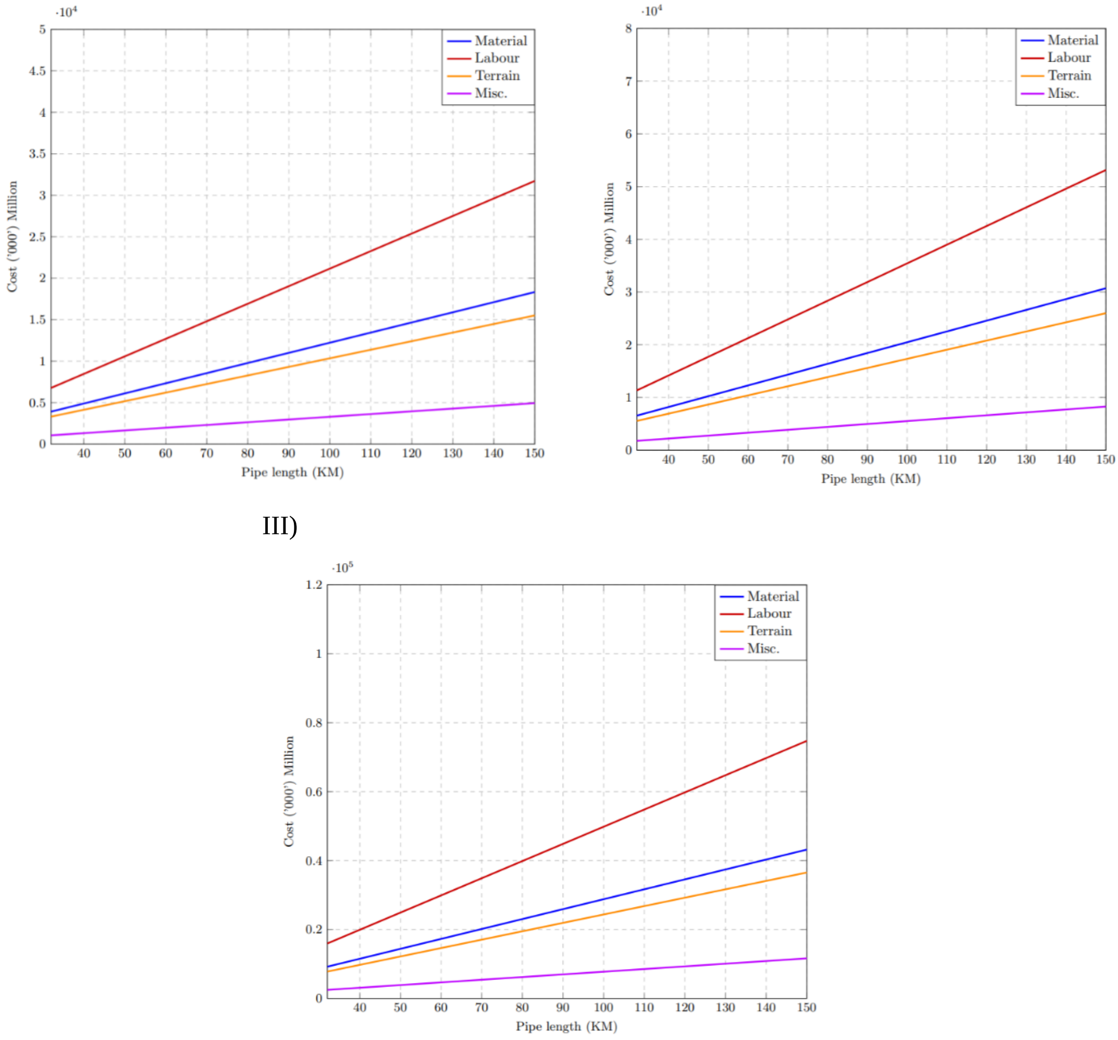
or

$$1\text{ km @12 inch} = \frac{3{,}321{,}428.57 \times 12}{36} = \text{US\$}1{,}107{,}142.86 \text{ (no compression)}$$

Table 28: Reference cost index 1 [145]

Composition	Percentage cost (%)
Material cost	26
Labour cost	45
Terrain cost	22
Miscellaneous	7

Four main reference costs index is used for option A as shown in Table 28 above. This is because the transportation infrastructure where the proposed alternative pathway is introduced is a new project which has already accounted for other costs.


I)

II)

III)

Figure 45: CAPEX using midstream, regional, and domestic cost estimates

The relief line has an estimated diameter of 12 inches. No compressor station is introduced for shorter pipeline distance in this study, and the proposed project already absorbs the permit costs. As stated earlier, the reference cost estimate reflects both regional and domestic cost estimates. However, the cost can be controlled when sufficient planning is established and the time frame for the complete installation is fixed. From the cost values expressed in Fig. 46, the effect on the NPV is further explained in section 6.2.

Option B: Retrofit cost to existing transportation infrastructure (existing project)

In option B, the gas mainline pipeline transportation project is already in operation for up to 10 years, and the remaining life span is 20 years. The NPV for this project is based on the remaining life of the existing pipeline. For option B, the additional pathway is introduced as a completely independent project such that the independent cost is expected to be recouped before the end of the pipeline life span. For this scenario, cost components are extended and are independent of the cost of the existing infrastructure (see Table 29). The permit cost is fixed for all project sizes, and all costs are represented in millions of dollars. The expected start date is 2020, with an expected completion date in 2022. The average inflation used is 12.44 percent per annum (p.a) with an interest on debt financing of 13.5 percent p.a.

Table 29: Reference cost index 2 [145]

Composition	Percentage cost (%)
Material cost	26
Labour cost	45
Terrain cost	22
Miscellaneous	7
<u>Additional cost:</u>	
Incremental labour cost (20% of 45%)	9
Tariff (40% of 26%)	10.4
Cost overrun	20
Average inflation (12.44% p.a)	12.44

Like option A, the relief line is the same with an estimated diameter of 12 inches. It is estimated that a compressor station installation will not be required because of the length of the pipeline. However, Table 30 below shows at what point the compressor plant can be considered. Table 31 is the reference estimates of the input parameters used.

Table 30: Compressor plant installation cost at every 80km

Diameter	length	No. of compressors	Horsepower	Cost of horsepower per compressor
12inch	80-150km	1	141 per every 1mmscfd	-

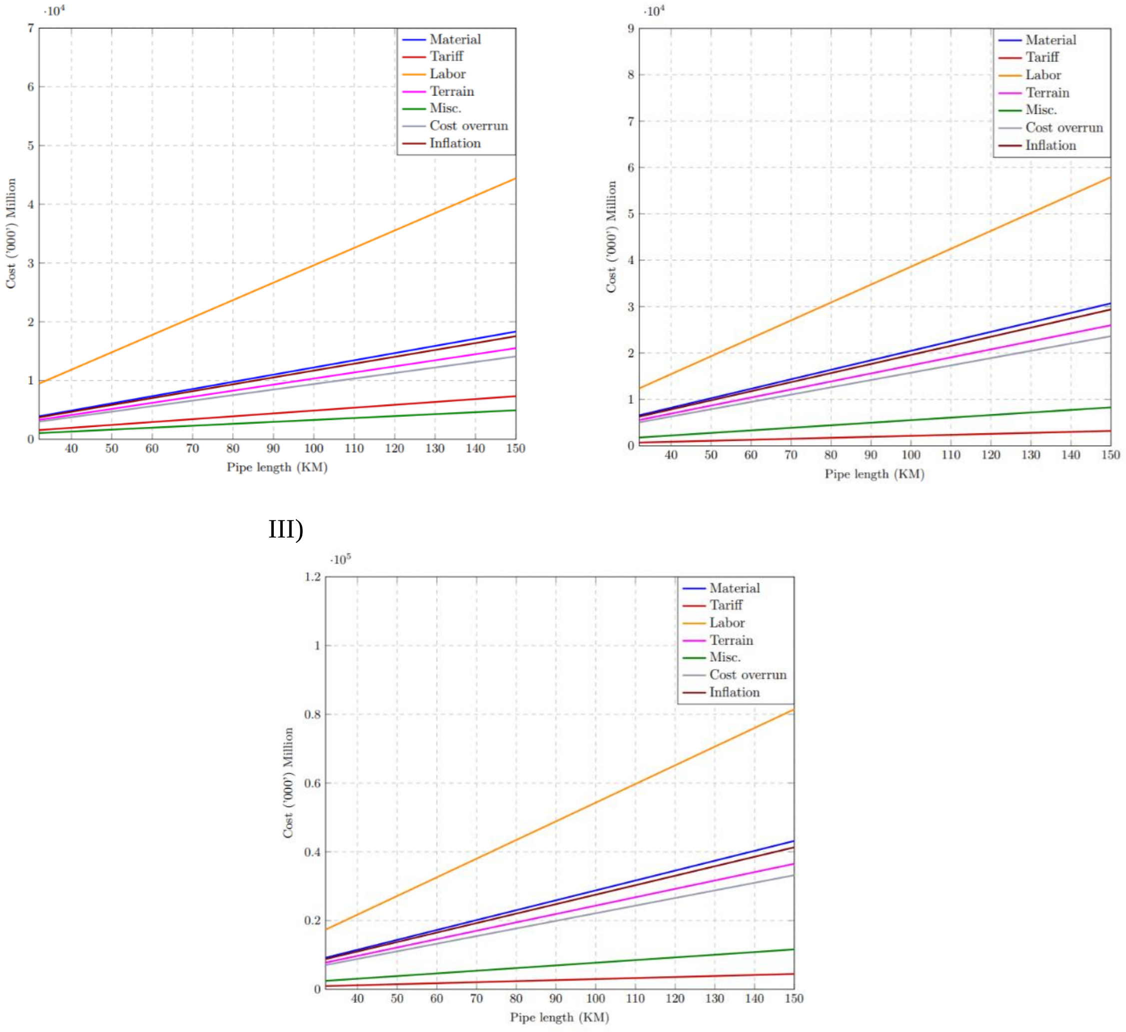

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Figure 46: CAPEX using midstream, regional, and domestic cost estimates

Table 31: Reference input parameter estimates

Description	Estimates (regional)	Estimates (domestic)
Total cost	US$10b + US$3b	US$1.860b
Length	4,128km	560km
Diameter	48 to 56inch	36inch
Cost per km	US$2,422,480.62 to US$3,149,224.81	US$3,321, 428.57
Capacity per year	30billion cubic feet = 30,000mmscfd	1,800mmscfd
Estimated relief pipeline size	12inch	12inch
Estimated length	32 to 150km	32 to 150km

8.1.2 Operating expenditure (OPEX)

The OPEX estimation includes fixed and variable costs such as administrative, repairs or maintenance, environmental permits, and energy cost. The OPEX calculated in this work is applicable for both existing and proposed pipeline infrastructure projects. For the relief pipeline, the OPEX comprises maintenance costs (valve testing and removal of surface inhibitions) over the plant's life span, personnel, insurance, and administrative costs, excluding fuel or energy costs. Fixed OPEX is an absolute value, while variable OPEX is a function of transported volume. The labour cost is generated at the prevailing exchange rate and is not subject to the pipeline's size. In this work, the labour cost of the average annual rate for both senior and junior engineers is accessed while the unit of labour for each pipeline length is assumed. Maintenance and environmental permit costs are usually fixed. The valve is essential during shutdowns and startup periods. The 'class 4' implies that a valve is installed for every 4 km of the pipeline. Each valve is changed at least once a year for the entire pipeline lifespan. In Table 32, the least cost estimate for operating expenditure is provided.

Table 32: Estimated operating expenditure for relief pipeline

Length (km)	Administrative cost (proposed project) (US$'000)	Administrative cost (existing project) (US$'000)	Environmental permit cost (US$'000)	Maintenance cost (US$'000)	Labour cost (US$'000)
32	300.839	456.191	814.332	63,000	205,212
40	376.049	570.235	814.332	78,900	205,212
50	470.062	712.790	814.332	98,625	205,212
75	705.093	1069.177	814.332	148,238	205,212
100	940.124	1425.564	814.332	197,550	205,212
125	1175.155	1781.951	814.332	247,163	205,212
150	1410.186	2138.338	814.332	296,475	205,212

8.1.3 Abandonment expenditure (ABEX)

ABEX involves the permanent deactivation and removal of the pipeline by the operators or the government at the end of the lifespan of the infrastructure. In this work, the ABEX also known as decommissioning cost is incurred towards the end of the active life of the asset. Many parameters affect the cost of decommissioning; therefore, in this work, the cost is based on standard estimates. The decommission cost forms part of the total cost estimate required to evaluate the economic performance of the proposed workflow. For some activities, the cost is identical for all pipeline sizes, while the cost varies for other activities. A thorough decommissioning cost (appendix 10) is calculated for each of the different project sizes to obtain a comprehensive cost estimate. See Tables 33 and 34 below. The ABEX has been calculated based on the different lengths of the proposed workflow. To calculate the NPV, the ABEX includes the comprehensive cost of pipeline removal. Total ABEX cost per inch based on the 32 inches pipe size is US$ 2,747, 000.

Table 33: Abandonment cost with pipeline removal (options A and B projects)

		Pipe size:	**32″**	**40″**	**50″**	**75″**	**100″**	**125″**	**150″**
	Description	calculation	Total (US$'000)	Total (US$'000)	Total (US$'000)	Total (US$'000)	Total (US$'000)	Total (US$'000)	Total (US$'000)
1	Engineering & project management cost	20% (168,000+42,000+504,000+35,000+4,800,000+50,000)	1119.80	1119.80	1119.80	1119.80	1119.80	1119.80	1119.80
2a	Land access and clean up	5250/km	168	210	262	393	525	656	787
2b	Pipeline purging & cleaning 1/4 for gas	1/4*168,000	42	42	42	42	42	42	42
3a	Basic abandonment in place	15,750/km	504	630	787.5	118.125	157.5	196.875	236.250
3b	Post abandonment activities	21,000/km	672	672	672	672	672	672	672
4	Special treatment (environmental)		35	35	35	35	35	35	35
5	Pipeline removal	150,000/km	4800	6000	7500	11250	15000	18750	22500
6	Above ground facilities		50	50	50	50	50	50	50
7	Contingencies	25% (168000+42000+504000+35000+4800000+50000)	1399.75	1699.75	2074.75	3012.25	3949.75	4887.25	5824.75
	Total		8790.55	10458.55	12543.55	17756.05	22968.55	28181.05	33393.55

Table 34: Abandonment cost without pipeline removal (options A and B projects)

		Pipe size:	**32″**	**40″**	**50″**	**75″**	**100″**	**125″**	**150″**
	Description	calculation	Total (US$'000)	Total (US$'000)	Total (US$'000)	Total (US$'000)	Total (US$'000)	Total (US$'000)	Total (US$'000)
1	Engineering & project management cost	20% (168,000+42,000+504,000+35,000+50,000)	159.80	159.80	159.80	159.80	159.80	159.80	159.80
2a	Land access and clean up	5250/km	168	210	262.5	393.75	525	656.25	787.5
2b	Pipeline purging & cleaning 1/4 for gas	1/4*168,000	42	42	42	42	42	42	42
3a	Basic abandonment in place	15,750/km	504	630	787.5	1181.25	1575	1968.75	2362.5
3b	Post abandonment activities	21,000/km	672	672	672	672	672	672	672
4	Special treatment (environmental)		35	35	35	35	35	35	35
5	Pipeline removal	150,000/km	0	0	0	0	0	0	0
6	Above ground facilities		50	50	50	50	50	50	50
7	Contingencies	25% (168000+42000+504000+35000+50000)	199.75	199.75	199.75	199.75	199.75	199.75	199.75
	Total		1830.55	1998.55	2208.55	2733.55	3258.55	3783.55	4308.55

8.1.4 Financial expenditure & weighted average cost of capital

As already established in subsection 8.1.1, two project options are compared in this chapter. Option A is an independent cost to a planned mainline gas transportation link, while option B is a retrofit cost to an existing mainline gas transportation infrastructure. Inflation is the rate at which the cost of the project increases. For this chapter, it is only applied to the retrofit cost. The reason is that it is an added cost to an already existing project. The WACC is the average after-tax cost of all capital sources for this project and represents the discount rate to calculate the NPV of the project. This means it reflects the cost of equity and cost of debt from which the cashflow will be discounted. Equity and debt are the two broad sources of capital. Inflation and capital and debt financing rate are introduced to account for the time value of money. The investment financial risks estimation and the source of the capital are considered when determining the discount rate [146]. The capital structure for the proposed gas infrastructure is 60/40 debt-equity ratio, while debt servicing is 13.5 percent p.a. The cost of the project can be affected by the source of project financing. By calculating the WACC, the management decision is whether to finance the project with debt or equity or with both.

$$\text{WACC} = \left(\frac{VE}{VF}\ x\ CoE\right) + \left(\frac{VD}{VF}\ x\ CoD\ x\,(1\ -\ \text{tr})\right)$$

where:

The market Value of Equity is represented as (VE), the market Value of Debt as (VD), the Cost of Equity as (CoE), the Cost of Debt as (CoD), the total Value of Financing as (VF), and Tax Rate as (tr). The cost of debt is represented by the debt financing interest rate for the project. The WACC for project A and B is 9.67 percent and 10.48 percent respectively (see appendix 7) with a 10 percent cost of equity, 13.5 percent cost of debt [147], and the statutory tax rate of 30 percent for the proposed project [148], and 20 percent for existing project. The expected result is that the calculated WACC should produce a positive NPV. The CoD is the current lending rate from the central bank accessed at the time of computation. The CoE is the interest-free rate on the government bond. The government bond varies based on the number of years. For instance, a 10-year bond yield is 10.974 percent, while a 20 year bond yield is 10.652 percent [149].

A 30-year bond yield can be higher or lower. A flat rate of 10 percent bond yield has been assumed to accommodate the life span of both A and B project options, respectively. Ideally, the CoE is expected to exceed the CoD as shareholders bear a higher risk than lenders to the project. From the calculation, the reverse is the case, this is because of higher default risk in repayment of loans from lenders due to uncertainty in funding in the country of study. Table 35 shows the equity and debt financing for both existing and new projects.

Table 35: Estimated cost for project financing

Length (km)	Debt financing proposed project (US$'000)	Debt financing existing project (US$'000)	Equity financing proposed project (US$'000)	Equity financing existing project (US$'000)
32	20552.33	21075.39	13701.55	14050.26
40	25161.81	25815.52	16774.54	17210.35
50	30923.58	31740.59	20615.72	21160.40
75	45328.18	46553.45	30218.78	31035.64
100	59732.59	61366.13	39821.73	40910.76
125	74137.19	76178.99	49424.79	50786.00
150	88541.61	90991.68	59027.74	60661.12

8.1.5 Cash flows

The inflow and outflow are required to determine the NPV of the project. The viability of the project becomes possible if positive cashflows are generated as opposed to negative cashflows. For this project, all cash flows are discounted to consider the time value of money. Discounting factors applied range from 0 to 20 percent; however, the WACC calculated, which must be between 0 to 20 percent, is used to determine the profitability of the project. The outflow includes the CAPEX, OPEX, and ABEX costs, whereas the inflow is the volume of improved throughput from the optimisation multiplied by the price of natural gas. For this chapter, the best-optimised throughput is used to estimate the project NPV, which is the mean optimised flow results in the steady state when the flow constraint is removed in the cumulative time.

8.2 Profitability measures

The net present value (NPV):

The NPV is a detailed profitability measure and a powerful tool employed to determine the discounted cashflow of the project. It is the present value of future incomes minus future costs for the project. The net cashflow is the difference in cash inflow from cash outflow during the life span of the project. The WACC, cost of the project, and the revenues accrued are the main factors determining whether the NPV will be zero, negative, or positive. In Table 36, the assumptions adopted for both options A and B are stated. The fundamental difference in the assumptions is in the life of the project, CAPEX, and WACC. For a detailed explanation for the difference, refer to 8.1.1 and 8.1.4. The NPV is calculated thus:

$$\mathbf{NPV} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \frac{\mathbf{Net\ cash\ flows_i}}{(\mathbf{1+r})^{\mathbf{i}}} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \frac{\mathbf{Net\ cash\ inflows_i}}{(\mathbf{1+r})^{\mathbf{i}}} - \mathbf{Initial\ outlay} \ldots$$

NPV ⟶ Net present value r ⟶ Discount rate (or WACC)
n ⟶ life of the project i ⟶ Number of time periods

Table 36: Basic assumptions for NPV calculation (Proposed and existing)

Parameter	Measurement unit	Assumption (proposed)	Assumption (existing)
Relief pipeline length	km	32	32
WACC	%	9.67	10.48
Project life	Years	30	20
CAPEX per km	US$’000	787.3	814.55
OPEX per km	US$’000	8.4	8.4
ABEX per km	US$’000	274.7	274.7
LOCE	US$	2.48	2.97
Debt proportion	%	60	60
Equity Proportion	%	40	40
Inflation	% (p.a)	13.5	13.5
Cost of debt	%	13.5	13.5
Cost of equity	%	10	10
Corporate tax	%	30	20

Discounted return on investment (ROI):

The discounted ROI is an approximate profitability measure. A more accurate ROI measure for long-term investments is the discounted ROI formula because it accounts for the time value of money. Therefore, the discounted ROI method considers the present value of future cash inflow and outflow by multiplying the cash flows by a discount rate or WACC.

$$\text{ROI} = \frac{\text{Discounted casf inflow} - \text{Discounted cost of investment}}{\text{Discounted cost of investment}}$$

$$= 152\%$$

8.2.1 Sensitivity analysis: Effect of WACC on NPV

The NPV is calculated against the revenue and base cost throughout the expected life of the pipeline node introduced (see appendix 11). Based on the CAPEX calculated for different pipeline lengths, the least cost with the best NPV is the pipeline with approximately 32 km. However, this also depends on the discounting factor or WACC. If the project is undertaken, the WACC is the rate at which the project is repaid after considering tax. The WACC is also used to determine the NPV. This means that the NPV varies at different WACC when applied to the different cost index for midstream, regional, and domestic cost estimates.

The WACC for option A’s proposed transportation infrastructure, as already calculated, is 9.67 percent for a life span of 30 years. The revenue from the least optimised throughput is used to determine the worst-case NPV. In the pessimistic state, a positive NPV of US$ 20,017.21million is generated over the lifespan of the project. This NPV is shown in Fig. 47 (I) using the reference cost index for midstream infrastructure, which is the benchmarked cost for global peer projects. For a further comparison using both regional and domestic cost estimates, and the result is shown in Fig. 48. The domestic cost estimate resulted in a negative NPV of US$ -373.32 million, as shown in (II). However, with the same WACC, the regional cost estimate provided a positive NPV of US$ 9,863.43 million, as shown in (III).

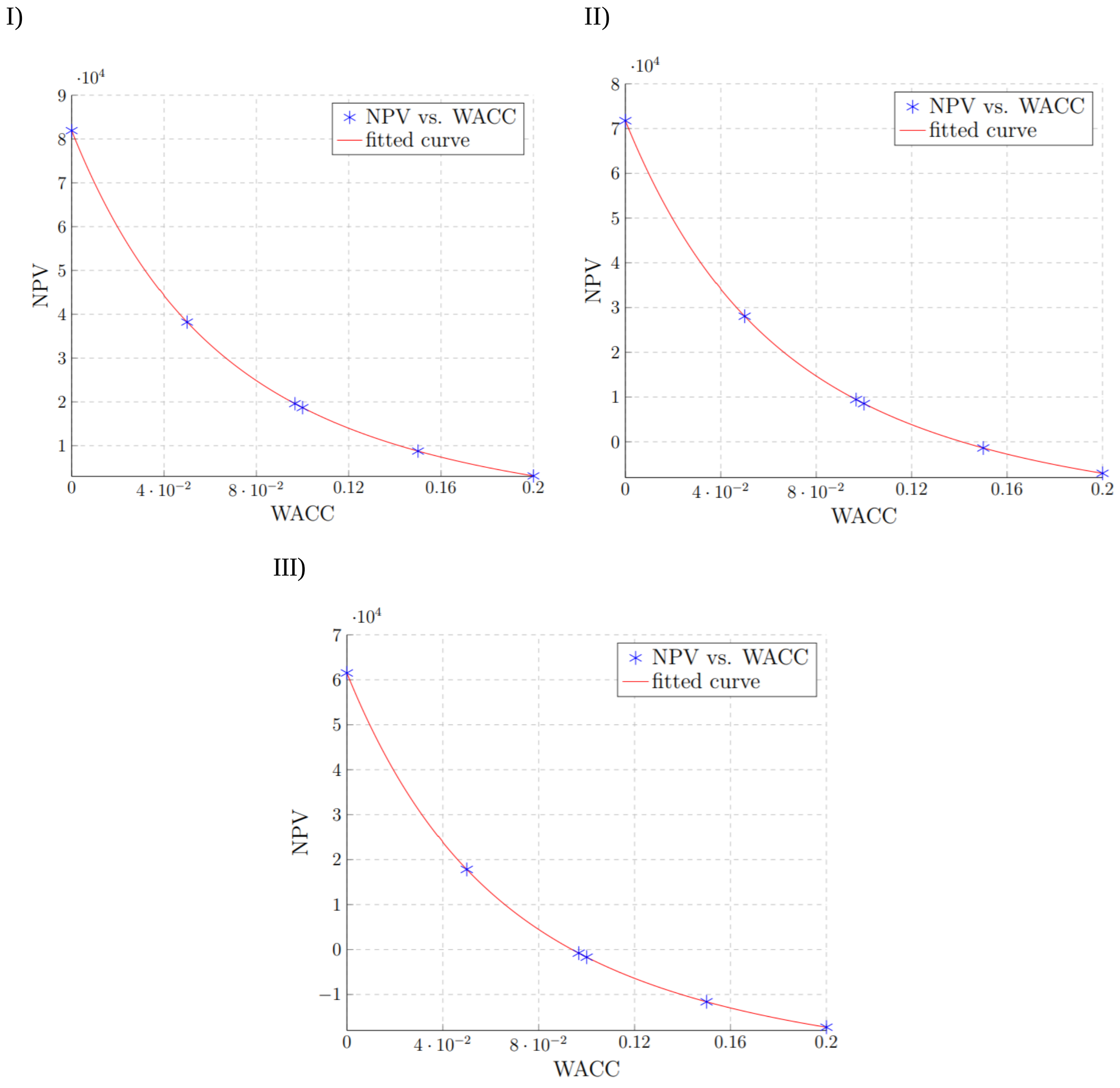


Figure 47: Performance of option A project using midstream, regional, and domestic cost estimates

A significant change is shown in the optimistic state if the cash inflow outlay, or revenue used is based on the most optimised throughput averaged for all periods. In this case, applying only the WACC on this outlay will give an NPV of US$ 26,624.68 million using the reference cost index for midstream infrastructure. The regional reference cost index produced a positive NPV of US$ 16,470.90 million, while with the domestic reference cost index, a positive NPV of US$ 6,234.15 million was produced.

Furthermore, the economic performance for the proposed relief pipeline is then analysed using the revenue from optimised throughput for option B. Like the independent cost in option A, the reference cost index for the midstream infrastructure in the pessimistic state shows a positive NPV of US$ 6,475.43 million with a WACC of 10.48 percent and a life span of 20 years. However, both the regional and domestic cost estimates showed a negative NPV of US$ -8,920.70 million and US$ -24,442.65 million, respectively, as shown in Fig. 48.

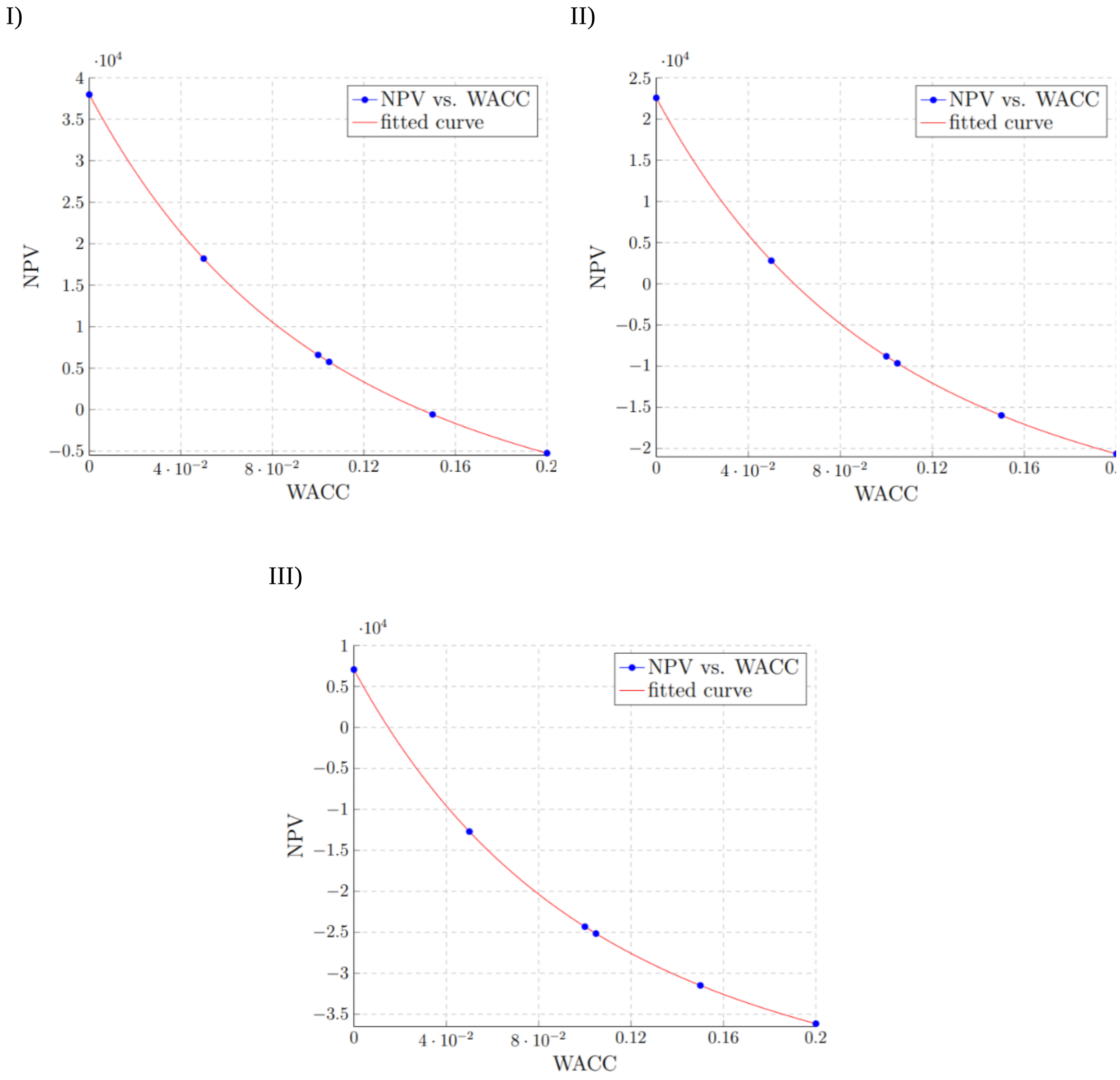


Figure 48: Performance of option B project using midstream, regional, and domestic cost estimates

Just like option A, if the revenue from the best possible optimised throughput is used to determine the net present value, then an NPV of US$ 11,890.25 million, US$ -3,505.88 million, and US$ -19,027.84 million for midstream infrastructure, regional, and domestic reference cost index respectively are obtained. By analysing the performances, it is safe to say that for both options, the effect of the WACC generates a positive NPV using the midstream reference estimate over the expected life span, indicating profitability for both the least and best optimised throughputs. Other reference cost estimates produced negative NPVs, and the cause of the negative NPVs is uncontrolled inflated pricing, defaults, and uncertainties. At this point, it is safe to say the type of reference cost that the decision-makers will adopt is very critical to the success of the optimised throughput with the introduction of the additional workflow.

Table 37: Table of fits

Project name	Data	SSE	R-square	DFE	Adj R-sq.	RMSE	No. Coeff.	Mean	Std
Proposed project	NPV vs WACC	0	1	0	NaN	NaN	999	0.0997	0.05762
Existing project	NPV vs WACC	0	1	0	NaN	NaN	1000	0.0999	0.05776

The line of best fit is introduced In Table 37. The line of best fit represents the relationship between the dependent variable and the corresponding independent variable(s). The sum of square due to error (SSE), which is the sum of the squared differences between each observation and its group's mean, shows a good fit for both options. The coefficient slightly differs for both projects, and it represents the degree of change in the dependent variable (NPV) for each additional unit in that variable. The degree of change represents the unknowns in the proposed projects. The mean fit line of 9.97 percent and 9.99 percent for options A and B are close to the WACC calculated as 9.67 percent and 10.48 percent. The standard deviation indicates how close the WACC of the individual project is to the mean. The near-zero standard deviations indicate the closeness of the WACC to the mean.

In addition to the table of fits is the sensitivity analysis which includes a spider diagram conducted to show the impact of +/-20 percent change of CAPEX on the NPV based on the existing infrastructure (option B) project. The percent change affects the individual CAPEX parameters used to determine the NPV while the WACC remains same.

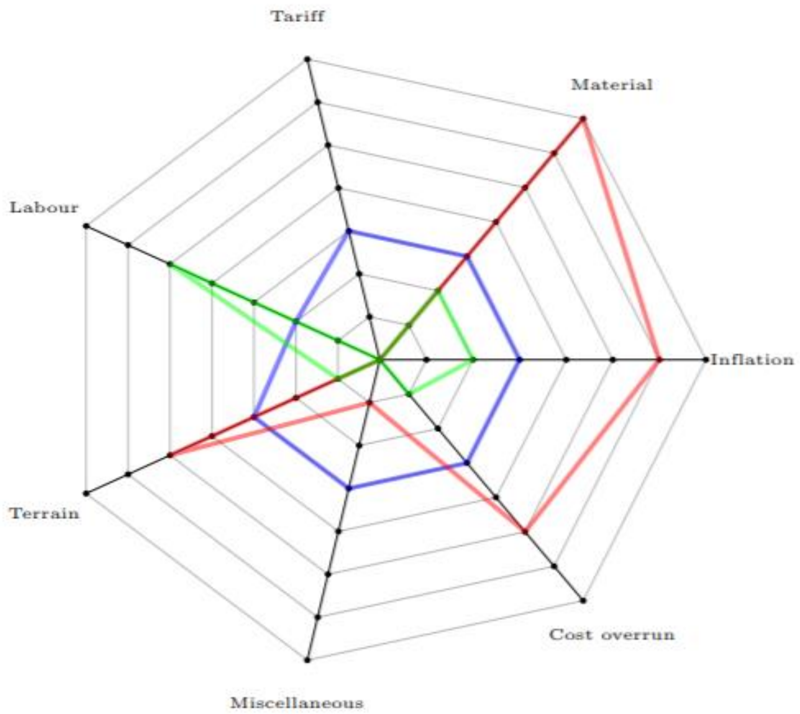


Figure 49: Spider diagram (7 dimensions, 7- notch scale, WACC vs. NPV)

The spider diagrams include seven parameters that are critical to determining the NPV of the project. Fig. 49 is a computation of +/- 20 percent change on the CAPEX of the midstream, domestic, and regional costs. The NPV based on the CAPEX of the individual cost component is measured against the + 20 change CAPEX on the NPV for the Midstream and domestic costs. The rationale is because it has been established that the midstream reference cost generates the best NPV while the domestic reference cost generates the worst NPV. The colour red represents the domestic reference cost that shows the change in NPV when CAPEX is increased to 20 percent. The colour green represents the midstream reference cost that shows the change in NPV when CAPX is increased to 20 percent, while colour blue represents the regional reference cost NPV without the change in WACC or CAPEX.

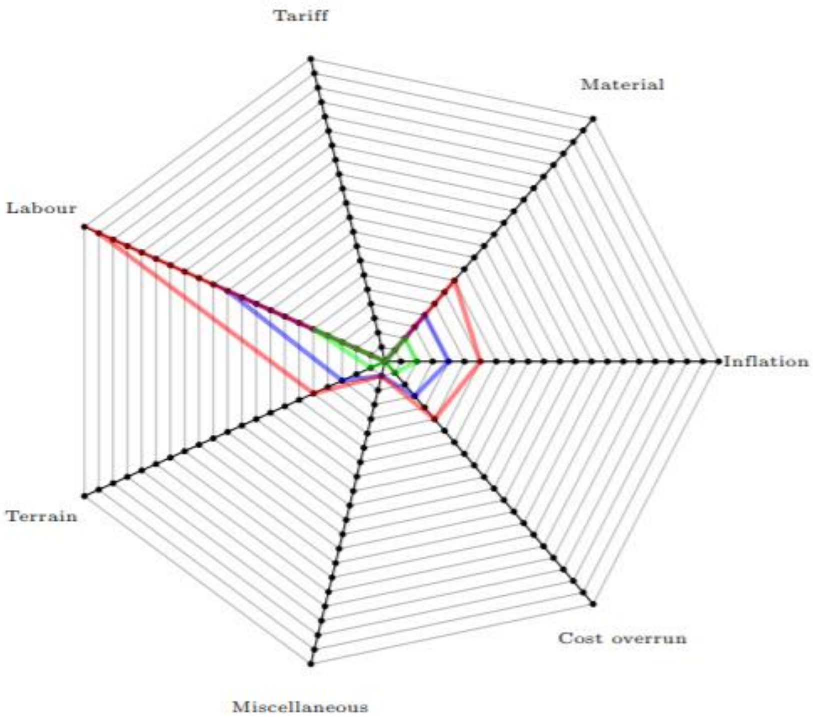


Figure 50: Spider diagram (7 dimensions, 21- notch scale, WACC vs. NPV)

Fig. 50 shows the degree of +/-20 percent change on the individual CAPEX parameter of the midstream, domestic, and regional cost on the NPV for the option B project. Seven parameters are used for the sensitivity analysis with a wider notch scale. The colours red, green, and blue represents the domestic, midstream, and regional reference cost estimates and they all depict the reaction of the NPV when the CAPEX is increased by 20 percent and WACC remains unchanged. For the option B project, the analysis shows that labour, material, and inflation are the major cost affected by the percentage change for all three reference cost estimates. Although the impact of reducing the CAPEX by – 20 percent is not shown in the diagram, preliminary investigation shows that the labour cost is hugely impacted across all three reference cost estimates.

8.3 Conclusion

This chapter explores the economic aspects of the proposed lateral relief pipeline on the studied natural gas supply chain. From the NPV and ROI, decision-makers can determine if the proposed alternative pathway should be introduced to a future planned project or an existing gas network. Although it is established in chapter three that the optimisation is on an existing supply chain, the cost estimation and comparison are made on both existing and new infrastructure for detailed economic analysis. Though a generally accepted localised assessment methodology for the costing may be currently unpracticable, a new assessment methodology is introduced by adopting the three different cost benchmark estimates presented in this chapter, which can be adopted for comparison when planning for pipeline infrastructure projects.

The comprehensive cost estimation calculated is based on the optimised flow rates obtained in chapters 5 and 6 to support investment decision making. The cost analysis is made on these two different independent projects. Results show that using domestic and regional estimates is not viable compared to using midstream reference cost estimates. Findings also show that option A which represents a new project has a higher net present value. This is because the life of the project is longer than the life of option B, inflation does not have a significant impact on the costs, and the discounting factor is lower than option B.

Consequently, in this chapter, we have established that the higher the WACC or discounting factor, the lower the present value of future cash flows and the lesser the NPV. Although option A performed better than option B, there is an additional life span of 10 years for option B. This means that there may be adequate cashflow from the disposal of the infrastructure. The sensitivity analysis is an indication that the WACC and the cost of investment are significant factors in determining the profitability of the project. Therefore, the lower the WACC, the higher the NPV. It means that to get a good NPV, the calculated WACC should not be unnecessarily high. Finally, the analysis shown in the spider diagram is an indication that the NPV is more sensitive to labour and material costs.

Chapter 9

Discussion, Conclusions, Recommendations for Future Work, and the Research Limitations

9.1 Research contribution

This study demonstrates how the natural gas supply chain can be improved by developing a resilience-driven novel optimisation model to maximise the gas throughput and minimise the associated CO_2 emissions. The model is applied to a case study, using field data collected from the industry. This research shows the importance of developing an optimisation framework that addresses the significant losses and shortages caused by disruptions to the gas supply chain midstream. The study delivers on the system's complementary design that enhances throughput delivery without disconnections, thereby investigating the retrofit benefit. In modelling the optimisation strategy, steady and transient states are analysed, and a comparison is made between both states, based on all scenarios introduced. Although the steady and transient states show improvements in the average throughput, the optimal solution signifying better throughput and savings on emission is achieved in the steady state using the same parameters. Furthermore, the best possible scenario (refer to Table 23) shows no significant trade-offs between costs and resilience in the economic analysis presented in chapter seven. This means that with the optimisation for resilience, the economic analysis shows a positive NPV with a high discounted ROI. In summary, the system-based strategy proposed in this study provides a two-fold solution to improve throughput and generate carbon savings. The proposed strategy shows an increased flow rate through continuous gas delivery, bringing about a reduction in loss and shortages caused by disruptions to the network. The best final solution shows a 93.6 percent optimised solution is achieved when the optimised throughput is compared with the expected flow rate to meet demand. Table 38 addresses the objectives sets out at the beginning of this work in chapter one.

Table 38: Scientific contribution

Set out objectives	Description of the contribution
Assemble a state-of-the-art literature review on energy supply chain resilience through optimisation.	The produced review paper responds to a single research question: What is the most appropriate and sustainable resilience strategy to tackle exogenous disruptions in energy supply chains.
Develop and apply a novel optimisation model to optimise a natural gas supply chain system in terms of its resilience.	1. This project develops a novel optimisation model that maximises throughput during disruptions and subsequent shutdown of nodes. The model considers resilience and CO2 emission savings as performance measures in a deterministic environment. 2. The developed model is applied to a real case study using data collected from the industry. Also, the model is applied to both steady and transient states of the gas supply chain.
Evaluate the lateral relief pipeline's impact as a proposed loss mitigation strategy on the natural gas supply chain.	The developed model investigates the impact of an additional design on the natural gas workflow to allow for contingencies without disconnections, thereby identifying its retrofit benefit that can yield increased throughput. The study also investigates the impact of the alternative pathway in the event of disruptions to a natural gas network node(s).
To estimate the profitability of the investment through a cost estimation model.	A broad analysis and extended financial evaluation are developed such that three different and independent reference cost estimates are used on both the new and existing project options. This gives infrastructure owners the leverage to decide on the more profitable venture.
To evaluate emissions savings after optimisation.	The CO_2 equivalent on the net emission savings from the optimised model is estimated.
To assess the impact of key parameters on the optimisation results by performing a sensitivity analysis study.	The analytical model is built to have the exact representation of an existing system. Also, the numerical result is used to conduct a sensitivity analysis as it relates to this study.

9.2 Conclusions

This research emphasises the need for a novel optimisation model for the gas supply chain in the transmission planning processes, which contemplates transport modelling characteristics with the inclusion of CO_2-eq savings. The gas loss reduction is limited to the trapped gas between the inlet and the outlet valves nodes on the mainline during an emergency shutdown. The research identifies the midstream echelon as critical because the pipeline and compressor nodes are pivotal in the gas supply chain's resilience decision. The mathematical programming optimisation for resilience proposed in this work concerning occurring and prolonged disruptions in the natural gas supply chain transmission line is applied in both steady and transient states. The relief pipeline is installed in a segment of the mainline where the cumulative capacity for expansion within the disruption time can be accommodated. The interactions between the nodes in the supply chain were adjusted to mitigate potential risks and increase efficiency. The optimisation indicates that the shutdown effect is fully minimised. The supply chain improvement is established in chapters five and six, where the result shows the effect of the proposed alternative pathway and the impact on demand and gas loss. Furthermore, the developed model and some modifications can be used to address other energy systems' resilience challenges, keeping in mind the peculiarity of the constraints, parameters, and variables of the different energy sources.

Five main pointers are identified as the core strategic relevance for this research. Firstly, there are possible structural changes in gas infrastructure to align with future policies on climate. For instance, researchers and industry experts currently argue that natural gas infrastructure can be repurposed in the future purely for hydrogen (H_2) transportation. Even as the research in Almansoori and Shah [150] shows that commercial quantity of hydrogen is generated from natural gas methane through the reforming process, Dodds and McDowall [151] argue that the decarbonisation of gas through H_2 conversion will enable gas networks to continue supplying energy for household consumption in the long-term. The researchers also argued that the utilisation of natural gas infrastructure for H_2 supply is cost effective. Apart from the conversion, MacKinnon, Brouwer, Samuelsen [17] stated that some researchers have suggested injecting H_2 without conversion to which will facilitate production, storage, large quantity transportation of H_2 which will help meet the net zero-emission target. This first pointer is critical because it provides the governments and decision-makers in the natural gas industry a strategic long-term opportunity for cost savings. After all, existing gas infrastructure may only require minimal modifications to be fully utilised for H_2 supply. The application of a well-thought-out strategy to other forms of energy, like H_2 and carbon capture and storage, is likely with the current natural gas infrastructure.

Secondly, the recent increase in carbon capture and storage (CCS) technologies have propelled gas supply chain resilience for flow flexibility and loss emission reduction.

Thirdly, as climate emissions increases, the gas transmission constraints may affect the transportation commitment and dispatch, paving the way for possible operational adjustments to gas infrastructure to align with future climate policies. The natural gas infrastructure is a key component if the legally binding commitment in the Paris agreement by the UNFCCC [152] to cut down on GHG is to be achieved to limit global warming effects.

Fourthly, prolonged emergency disruption will affect supply in the absence of an adequate backup strategy.

Fifthly, for pipeline transportation, a resilient supply chain is critical as other forms of energy like biogas and synthetic natural gas (SNG) may be injected and supplied through the natural gas infrastructure.

9.3 Recommendations for future work and limitations

The following recommendations are provided for future studies. Identifying the most appropriate location to introduce alternative pathways depending on the network's need over the planning horizon to satisfy demand and loss reduction should be considered. Also, the need to introduce and adopt new, economically viable technologies cannot be overemphasised at this point. Further research modelling should consider savings on downtime and how minimising the downtime will lead to profit maximisation for the firm. Finally, a similar study should be carried out in a stochastic environment where logical consideration of uncertainty can help estimate future expectations, calculate likely returns, and estimate associated risks. Much more is required from proposed models to begin to introduce sustainability as a critical objective function as it relates to system interruptions.

Certain likely limitations have been identified in this work. One of the limitations is that the result and final output may vary when different parameters and characteristics are introduced in the modelling. Although the model is run on a short distance network, it is assumed that this model can be further applied to a long-distance network and in environments with similar characteristics. Also, identifying the best possible location for the proposed backup strategy is critical to achieving optimal results as wrong location decisions may pose a significant challenge. In the light of the above, the research identifies the transmission echelon as the ideal location for the proposed workflow. Location specificity is required from the operators of the supply chain which has not been provided in this study. Although uncertainties are likely occurring factors to account for disruption, this research does not provide detailed historical trend analysis to project and estimate potential uncertainties. Finally, the research is tailored as a multi-objective function. However, the attributes of the objective function are not optimised individually.

Appendices

Appendix 1

Data of gas transported through company xxx

CONTRACTUAL VOLUME OBLIGATION (MMscf/d)	2016 Gas Price/ Trans. Tariff ($/Mscf)	2017 Gas Price/ Trans. Tariff ($/Mscf)	2018 Gas Price/ Trans. Tariff ($/Mscf)	SECTOR	ACTUAL GAS DELIVERED (MMscf/d)													
					Jan-16	Feb-16	Mar-16	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17
360.00	3.30	3.30	3.30	Power	226.19	200.79	157.03	120.72	95.95	76.31	72.16	91.29	109.21	120.59	120.59	71.35	69.14	73.95
	3.30	3.30	3.30	Power	15.81	18.35	8.66	11.25	6.61	12.71	18.42	19.96	14.36	18.60	5.32	19.50	18.63	17.97
	3.30	3.30	3.30	Power	51.97	13.02	44.77	16.09	4.55	0.00	2.51	12.43	15.76	18.99	18.07	10.00	15.44	34.09
	3.30	3.30	3.30	Power	47.67	29.34	0.00	4.13	14.88	15.51	17.19	20.41	23.16	30.77	25.98	27.39	32.34	39.53
	3.30	3.30	3.30	Power	63.38	40.55	29.63	24.16	19.07	11.47	19.63	27.59	42.15	46.88	28.98	26.90	26.35	41.43
	3.30	3.30	3.30	Power	53.04	33.36	28.69	0.00	13.28	4.09	19.41	23.31	38.40	40.35	0.00	0.00	21.06	30.73
	3.30	3.30	3.30	Power	3.76	1.27	2.28	19.99	14.42	13.70	26.79	27.96	28.95	27.37	28.21	25.17	4.23	2.93
	3.30	3.30	3.30	Power	19.86	24.30	22.27	27.55	18.71	15.54	13.65	21.15	22.45	27.51	25.41	25.10	16.24	28.72
	3.30	3.30	3.30	Power	42.32	35.19	30.87	7.01	13.09	9.50	0.00	0.00	26.40	45.99	24.78	25.05	19.51	36.16
	3.30	3.30	3.30	Power	25.48	0.00	12.13	26.61	10.99	9.06	23.91	28.57	26.36	23.31	27.91	30.43	16.06	27.57

	3.30	3.30	3.30	Power	20.73	28.40	26.49	28.35	21.36	13.76	20.26	31.10	29.91	9.56	23.75	25.82	17.95	41.45
	0.80	0.80	0.80	Power	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					570.21	**424.56**	**362.83**	**285.87**	**232.89**	**181.65**	**233.93**	**303.75**	**377.11**	**409.91**	**329.00**	**286.71**	**256.93**	**374.54**
	3.56 - 7.36	3.59 - 7.45	3.68 - 7.62	Commercial	262.71	236.73	243.73	252.84	170.07	145.28	160.06	199.95	232.63	253.75	225.63	208.37	187.05	227.08
4.50	0.72	0.72	0.74	Transportation	0.97	1.34	1.19	1.01	1.11	1.09	0.99	0.75	0.70	0.77	0.61	1.27	1.08	1.02
	1.14	2.98	2.98	Transportation	0.00	0.89	0.00	1.54	0.00	0.00	0.00	0.70	0.67	0.37	0.74	0.75	0.74	1.04
133.00	1.30	1.31	1.3393	Transportation	38.21	23.85	18.55	29.67	12.32	2.13	0.84	26.49	29.51	30.88	29.29	27.46	17.59	15.42
15.00	2.36	2.39	2.39	Transportation	39.47	40.63	33.37	18.27	4.94	16.39	19.98	1.38	3.99	0.00	3.32	17.63	29.84	32.87
	1.14	1.15	1.18		0.00	3.94	0.00	4.58	3.86	2.31	0.00	0.00	3.11	2.06	4.03	3.55	3.21	4.58
					78.65	**70.65**	**53.11**	**55.07**	**22.23**	**21.92**	**21.81**	**29.31**	**37.98**	**34.08**	**37.99**	**50.65**	**52.45**	**54.94**
33.00	3.30	3.30	3.30	Power	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40.00	0.80	0.80	0.80	Power	1.75	30.82	20.65	1.48	77.27	25.17	0.00	17.87	14.93	9.71	0.00	10.12	11.84	21.56
					24.29	23.12	0.00	0.00	0.00	0.00	0.00	0.00	18.44	19.79	0.00	0.00	0.00	0.00
					1.75	**30.82**	**20.65**	**1.48**	**77.27**	**25.17**	**0.00**	**17.87**	**14.93**	**9.71**	**0.00**	**10.12**	**11.84**	**21.56**

7.31	3.94	3.98	4.07	Commercial	3.71	4.60	3.96	5.03	4.60	0.89	0.00	2.87	2.15	0.04	3.81	3.68	4.11	4.70
50.00	0.30	0.30	0.30	Gas Based Industry	40.38	25.65	43.09	0.00	47.04	37.50	0.00	46.54	42.40	43.65	19.48	38.70	50.85	45.99
23.00				Commercial	0.00	0.00	0.00	0.00	10.63	0.00	0.00	0.00	19.11	27.73	0.00	0.00	0.00	0.00

CONTRACTUAL VOLUME OBLIGATION (MMscf/d)	2016 Gas Price/ Trans. Tariff ($/Mscf)	2017 Gas Price/ Trans. Tariff ($/Mscf)	2018 Gas Price/ Trans. Tariff ($/Mscf)	SECTOR	ACTUAL GAS DELIVERED (MMscf/d)															
					Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18	Apr-18	May-18	Jun-18
	3.30	3.30	3.30	Power	82.13	74.30	91.62	113.01	142.59	150.59	84.01	89.33	103.99	152.93	103.13	138.59	140.41	141.95	130.97	129.03
	3.30	3.30	3.30	Power	3.55	11.10	19.76	15.40	14.90	20.94	18.09	21.36	8.37	0.00	0.00	1.42	17.62	12.81	13.26	9.17
	3.30	3.30	3.30	Power	36.35	49.82	49.34	43.33	41.43	40.33	50.25	81.59	48.07	55.89	59.72	93.10	90.04	73.34	71.76	84.85
	3.30	3.30	3.30	Power	34.65	49.03	52.92	66.23	52.76	38.81	42.48	46.14	51.29	64.74	49.82	62.57	39.46	58.32	32.98	42.19
	3.30	3.30	3.30	Power	49.73	41.76	35.64	45.88	39.51	39.51	28.98	38.97	41.34	42.10	26.69	35.98	42.11	45.59	35.13	39.50
	3.30	3.30	3.30	Power	34.15	40.46	42.16	48.15	32.90	30.11	34.00	38.22	40.36	39.94	30.21	39.78	33.45	38.32	34.43	36.64
	3.30	3.30	3.30	Power	3.61	2.75	10.48	44.43	29.97	26.93	35.53	27.93	39.15	40.92	7.56	45.95	3.45	21.17	11.03	10.54

	3.30	3.30	3.30	Power	46.19	38.36	27.86	18.72	21.91	17.42	22.46	35.47	43.16	43.92	43.47	44.19	45.73	39.12	38.41	34.47
	3.30	3.30	3.30	Power	39.66	35.63	25.30	32.16	26.93	25.77	27.22	32.24	27.16	32.39	28.34	40.40	33.43	27.84	26.82	32.90
	3.30	3.30	3.30	Power	25.52	28.51	26.29	31.98	28.24	25.55	25.20	27.43	30.11	31.88	33.70	39.61	40.49	39.14	10.34	10.34
	3.30	3.30	3.30	Power	27.80	33.57	36.57	32.14	25.91	20.88	22.74	24.65	23.42	23.63	23.72	8.46	25.45	21.70	26.98	34.59
	0.80	0.80	0.80	Power	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.35	1.71	6.25	25.08	69.19	72.36
					383.32	**405.31**	**417.94**	**491.42**	**457.04**	**436.83**	**390.96**	**463.33**	**456.44**	**528.33**	**407.73**	**551.76**	**517.90**	**544.39**	**501.29**	**536.59**
	3.56 - 7.36	3.59 - 7.45	3.68 - 7.62	Commercial	255.29	236.69	253.76	230.22	233.91	213.08	220.31	239.46	267.35	264.30	182.30	277.17	272.04	272.57	265.76	263.03
4.50	0.72	0.72	0.74	Transportation	1.17	1.22	1.13	1.21	1.11	1.21	1.07	1.09	0.07	0.13	0.12	1.25	1.00	0.99	0.92	1.10
	1.14	2.98	2.98	Transportation	0.74	0.99	0.92	0.10	0.91	0.80	0.77	0.85	0.98	0.60	0.83	0.81	0.73	0.90	0.67	0.78
133.00	1.30	1.31	1.3393	Transportation	18.67	23.75	23.99	39.90	44.40	57.97	63.09	51.26	49.36	45.29	39.02	47.23	77.14	88.83	49.97	47.50
15.00	2.36	2.39	2.39	Transportation	31.45	30.24	19.17	35.72	42.66	38.65	40.48	37.77	26.51	37.48	29.87	32.02	35.60	44.81	43.51	42.55
	1.14	1.15	1.18		3.32	0.00	0.00	0.66	3.29	3.06	0.00	4.01	3.95	2.79	3.20	3.42	3.14	2.57	2.91	3.37
					55.34	**56.21**	**45.21**	**77.59**	**92.36**	**101.69**	**105.41**	**94.98**	**80.87**	**86.29**	**73.04**	**84.71**	**117.60**	**138.10**	**97.98**	**95.31**

33.00	3.30	3.30	3.30	Power	0.00	0.00	0.00	0.00	0.00	0.00	5.15	9.57	11.44	15.44	15.38	10.39	17.61	9.67	10.90	11.44
40.00	0.80	0.80	0.80	Power	24.79	10.98	25.34	10.96	13.76	11.70	15.28	21.94	2.67	0.00	0.00	0.00	0.00	0.00	6.21	22.16
					0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					24.79	**10.98**	**25.34**	**10.96**	**13.76**	**11.70**	**20.42**	**31.50**	**14.11**	**15.44**	**15.38**	**10.39**	**17.61**	**9.67**	**17.11**	**33.60**
7.31	3.94	3.98	4.07	Commercial	3.40	4.34	5.22	0.27	1.82	2.37	3.77	4.56	2.79	3.47	4.10	3.61	3.36	5.01	3.27	3.67
50.00	0.30	0.30	0.30	Gas Based Industry	41.30	50.08	41.79	47.97	48.54	48.06	39.44	45.74	41.63	38.53	36.29	32.60	29.80	33.20	42.06	33.13
23.00				Commercial	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 2

Data parameters analysed for evaluation

Raw data collected are processed, and all relevant parameters extracted.

DEMAND OBLIGATION (mmscfd) d_b		mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd	mmscfd
MONTH	Total	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16
Power Plant	**10800**	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00	360.00
Commercial	**219.3**	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31
Industrial	**1500**	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50	50.00
ACTUAL SUPPLY (mmscfd)																	
MONTH	**Total**	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16
Power Plant	**3473.85**	226.19	200.79	157.03	120.72	95.95	76.31	72.16	*91.29*	109.21	120.59	120.59	71.35	69.14	73.95	82.13	74.30
Commercial	**99.20**	3.71	4.60	3.96	5.03	4.60	0.89	0.00	2.87	2.15	0.04	3.81	3.68	4.11	4.70	3.40	4.34
Industrial	**1131.44**	40.38	25.65	43.09	0.00	47.04	37.50	0.00	46.54	42.40	43.65	19.48	38.70	50.85	45.99	41.30	50.08
shortage		133.81	159.21	202.97	239.28	264.05	283.69	287.84	268.71	250.79	239.41	239.41	288.65	290.86	286.05	277.87	285.70
	Total																
% of shortfall (power plant)	**7326.15**	0.37	0.44	0.56	0.66	0.73	0.79	0.80	1.25	1.30	1.33	0.67	0.80	0.81	0.79	0.77	0.79
% of shortfall(commercial)	**120.1**	0.49	0.37	0.46	0.31	0.37	0.88	1.00	1.39	1.29	1.00	0.48	0.50	0.44	0.36	0.54	0.41

% of shortfall (industrial)	**368.56**	0.19	0.49	0.14	1.00	0.06	0.25	1.00	1.93	1.85	1.87	0.61	0.23	-0.02	0.08	0.17	0.00
	7814.81																
CAPACITY																	
gas Plants		*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*
compressor		*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*
city gate		*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*
storage		*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*
Gas supplier		*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*
no of gas suppliers (subset IH)		*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
no of gas plants		*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
no of compressor station		*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*
no of city gates		*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
no of storage		*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
no of pipeline		*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*
Gas operation																	
No of hours per day for process flow	24hrs/day																
Cost of downtime	$100,000/hr																
Frequency of plant shutdown	?																
No. of time during shutdown	?																
Pipeline (between pipeline and consumer)																	
Cost of 1km of pipeline (or 50km or 100km)																	

pipeline capacity	400(mscfd)
Length	34KM
Inch	36 Inc
max pressure	1000 psi
min pressure	700 psi
temperature	60°F
Power plant	
Rate of shortage (ROS)	30/30= 1
number of shortages over period of consideration/ number of months	
Average shortage:	
total shortage in percentage/ number of months	20.35/30= 0.67
Mass flow rates	mmscfd
gas field (operating pressure)	450
gas plant (operating pressure)	450
compressor (operating pressure)	300

ACTUAL SUPPLY (mmscfd)														
MONTH	t17	t18	t19	t20	t21	t22	t23	t24	t25	t26	t27	t28	t29	t30
Power Plant	91.62	113.01	142.59	150.59	84.01	89.33	103.99	152.93	103.13	138.59	140.41	141.95	130.97	129.03
Commercial	5.22	0.27	1.82	2.37	3.77	4.56	2.79	3.47	4.10	3.61	3.36	5.01	3.27	3.67
Industrial	41.79	47.97	48.54	48.06	39.44	45.74	41.63	38.53	36.29	32.60	29.80	33.20	42.06	33.13
shortage	268.38	246.99	217.41	209.41	275.99	270.67	256.01	207.07	256.87	221.41	219.59	218.05	229.03	230.97
% of shortfall (power plant)	0.75	0.69	0.60	0.58	0.77	0.75	0.71	0.58	0.71	0.62	0.61	0.61	0.64	0.64
% of shortfall(commercial)	0.29	0.96	0.75	0.68	0.48	0.38	0.62	0.53	0.44	0.51	0.54	0.31	0.55	0.50
% of shortfall (industrial)	0.16	0.04	0.03	0.04	0.21	0.09	0.17	0.23	0.27	0.35	0.40	0.34	0.16	0.34
CAPACITY														
gas Plants	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*	*1040.00*
compressor	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*	*500.00*
city gate	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*	*200.00*
storage	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*	*50.00*
gas supplier	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*	*1345.00*
no of gas suppliers (subset IH)	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
no of gas plants	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
no of compressor station	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*	*4.00*
no of city gates	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
no of storage	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
no of pipeline	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*

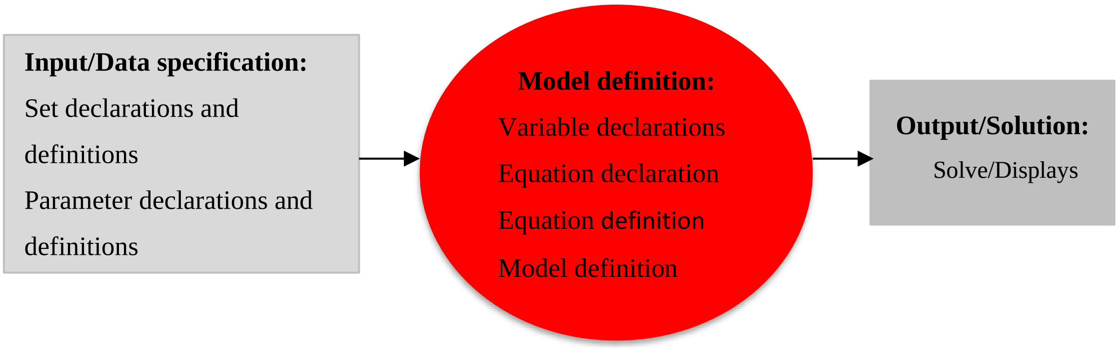
Appendix 3

Constraints and GAMS flowchart

A summary of all constraints introduced is shown in the table and a simple flowchart is added which highlights how GAMS is modelled.

Summary of constraints

N/O	Description
I.	Shutdown and startup
II.	Supplier and production capacity constraints
III.	Compressor capacity constraint.
IV.	City gate capacity constraint
V.	Power plant capacity constraint.
VI.	Demand constraints
VII.	Storage constraint
VIII.	Mass balance law constraint
IX.	Pipeline pressure constraint
X.	Pressure inequality constraint
XI.	Incremental capacity expansion constraints
XII.	Flow constraints
XIII.	Shortage/loss constraints



Appendix 4

Sample of Solve data log

Several iterations were implemented in the code using the CPLEX LINK licenced to solve continuous and discrete problems. Below is a sample of one of the iterations that provided optimised solution.

```
Reading data...
Starting Cplex...
Space for names approximately 0.28 Mb
Use option 'names no' to turn use of names off
CPXPARAM_Advance                                 0
CPXPARAM_Simplex_Limits_Iterations               3600000
CPXPARAM_TimeLimit                               20000000
CPXPARAM_WorkDir                          "C:\Users\2442351e\Documents\gamsdir\projdir\225a\"
CPXPARAM_Threads                                 1
CPXPARAM_Parallel                                1
CPXPARAM_Tune_TimeLimit                          4000000
CPXPARAM_MIP_Tolerances_AbsMIPGap                0
CPXPARAM_MIP_Tolerances_MIPGap                   0
CPXPARAM_MIP_Display                             4
Tried aggregator 2 times.
MIP Presolve eliminated 3722 rows and 3040 columns.
MIP Presolve modified 735 coefficients.
Aggregator did 224 substitutions.
Reduced MIP has 1750 rows, 2759 columns, and 7922 nonzeros.
Reduced MIP has 457 binaries, 0 generals, 0 SOSs, and 0 indicators.
Presolve time = 0.06 sec. (10.86 ticks)
Found incumbent of value 5276672.000000 after 0.08 sec. (14.31 ticks)
Probing time = 0.00 sec. (1.02 ticks)
Tried aggregator 1 time.
MIP Presolve eliminated 796 rows and 1536 columns.
Reduced MIP has 954 rows, 1223 columns, and 3362 nonzeros.
Reduced MIP has 457 binaries, 0 generals, 0 SOSs, and 0 indicators.
Presolve time = 0.02 sec. (6.31 ticks)
Probing time = 0.00 sec. (0.94 ticks)
Clique table members: 1205.
MIP emphasis: balance optimality and feasibility.
MIP search method: dynamic search.
Parallel mode: none, using 1 thread.
Tried aggregator 1 time.
No LP presolve or aggregator reductions.
Presolve time = 0.00 sec. (0.54 ticks)
Initializing dual steep norms . . .

Iteration log . . .
Iteration:     1   Dual objective     =      95239460.000000
Iteration:   142   Dual objective     =      83959073.000000
Iteration:   241   Dual objective     =      83958961.000000
Iteration:   328   Dual objective     =      83958745.000000
```

```
Iteration:   429   Dual objective     =      83958619.000000
Iteration:   532   Dual objective     =      83958541.000000
Iteration:   643   Dual Objectives     =      83958477.000000
Root relaxation solution time = 0.01 sec. (6.93 ticks)



  Nodes                                                                Cuts/
                Node Left     Objective IInf Best Integer    Best Bound    ItCnt     Gap

*     0+            0                                 5276672.0000   1.23556e+08              ---
Found incumbent of value 5276672.000000 after 0.22 sec. (31.28 ticks)
      0              0   8.39585e+07   151 5276672.0000     8.39585e+07      698          ---
*     0+    0                     8.39582e+07   8.39585e+07            0.00%
Found incumbent of value 8.3958217e+07 after 0.22 sec. (33.23 ticks)
      0     0                8.39585e+07   118   8.39582e+07     Cuts: 105      778        0.00%
*     0+    0                                    8.39583e+07   8.39585e+07              0.00%
Found incumbent of value 8.3958305e+07 after 0.28 sec. (58.70 ticks)
      0     0   8.39585e+07    80                8.39583e+07     Cuts: 243      869        0.00%
      0     0   8.39585e+07    88   8.39583e+07     Cuts: 203      909    0.00%
*     0+    0                                     8.39584e+07   8.39585e+07             0.00%
Found incumbent of value 8.3958385e+07 after 0.31 sec. (86.10 ticks)
      0     0   8.39585e+07    58                 8.39584e+07     Cuts: 184      942       0.00%
*     0     0      integral     0                          8.39585e+07     Cuts: 84      945    0.00%
Found incumbent of value 8.3958457e+07 after 0.33 sec. (95.75 ticks)
      0     0       cutoff                      8.39585e+07       8.39585e+07      945     0.00%
Elapsed time = 0.33 sec. (95.75 ticks, tree = 0.01 MB, solutions = 5)



Clique cuts applied:  384
Implied bound cuts applied:  4
Flow cuts applied:  2
Mixed integer rounding cuts applied:  16
Zero-half cuts applied:  15
Lift and project cuts applied:  13
Gomory fractional cuts applied:  16

Root node processing (before b&c):
Real time            =    0.34 sec. (96.16 ticks)
Sequential b&c:
Real time            =    0.00 sec. (0.00 ticks)
                          ------------

Total (root+branch&cut) =    0.34 sec. (96.16 ticks)
MIP status(101): integer optimal solution
Cplex Time: 0.34sec (det. 96.17 ticks)
Fixing integer variables, and solving final LP...
CPXPARAM_Advance                                     2
CPXPARAM_Simplex_Limits_Iterations              3600000
CPXPARAM_TimeLimit                             20000000
CPXPARAM_Threads                                       1
CPXPARAM_Parallel                                      1
CPXPARAM_Tune_TimeLimit                        4000000
CPXPARAM_MIP_Tolerances_AbsMIPGap               0
CPXPARAM_MIP_Tolerances_MIPGap                  0
CPXPARAM_MIP_Display                                  4
Tried aggregator 1 time.
LP Presolve eliminated 4338 rows and 3721 columns.
```

```
Reduced LP has 1358 rows, 2302 columns, and 6550 nonzeros.
Presolve time = 0.00 sec. (3.76 ticks)


Iteration log . . .
Iteration:     1   Dual infeasibility =            0.000000
Iteration:     2   Dual objective     =       95238844.000000
Iteration:    63   Dual objective     =      95238844.000000
Perturbation started.
Iteration:   103   Dual objective     =      95238844.000000
Iteration:   165   Dual objective     =      95238843.991238
Iteration:   266   Dual objective     =      87144456.981184
Removing perturbation.
Fixed MIP status(1): optimal
Cplex Time: 0.03sec (det. 15.23 ticks)


Proven optimal solution.


MIP Solution:     83958457.000000    (945 iterations, 0 nodes)
Final Solve:      83958457.000000       (371 iterations)

Best possible:    83958457.000000
Absolute gap:           0.000000
Relative gap:            0.000000


--- Restarting execution
--- Run_DATA.gms(790) 2 Mb
--- Reading solution for model gas_supply_chain
--- Run_DATA.gms(790) 3 Mb
--- Executing after solve: elapsed 0:00:03.556
--- Run_DATA.gms(816) 4 Mb
*** Status: Normal completion
--- Job Run_DATA.gms Stop 06/30/20 15:26:16 elapsed 0:00:03.571
```

Appendix 5

Cost parameters

Based on the total reference cost unit cost for midstream, domestic, and regional infrastructure, the unit cost per km of pipeline is calculated.

Description	Domestic pipeline estimate	Regional pipeline estimate
Year of installation (WiP)	2020	2020
Life span expectation	30 years	30 years
Introduction of relief	2021	2021
Life span of relief	30 years	30 years
Expected payback period	-	-
Reference total cost of project	US$1.860B	US$10b + US$3b
Reference cost for 1km	US$3.321M	US$2.422 M to US$3.149M
Length of total project	560km	4,128km
Capacity of total project	1,800 mmscfd	30,000mmscfd
Size (diameter)	36 inches	48 to 56inch

Using domestic pipeline estimate: if 1km @36inch = 3,321,428.57 (upper limit)

Then:

1km @at 12 inches

$$\frac{3,321,428.57}{36} \quad X \quad 12 = \quad \text{US\$1,107,142.86}$$

Using regional pipeline estimate: if 1km @48inch = 3,149,224.81 (upper limit)

Then:

1km @at 12 inches

$$\frac{3,149,224.81}{48} \quad X \quad 12 = \quad 787,306.20$$

Using midstream cost estimate:

Total cost per mile 63,041
Then:
1km @at 12 inches
63,041.00 X 12 X 0.621371 = 470,062.19

Appendix 6

Cost composition

Each cost element is determined based on the cost composition for 1km of pipeline. The cost component for option B is broader as it forms an incremental cost to an existing project.

(new project) Option A:

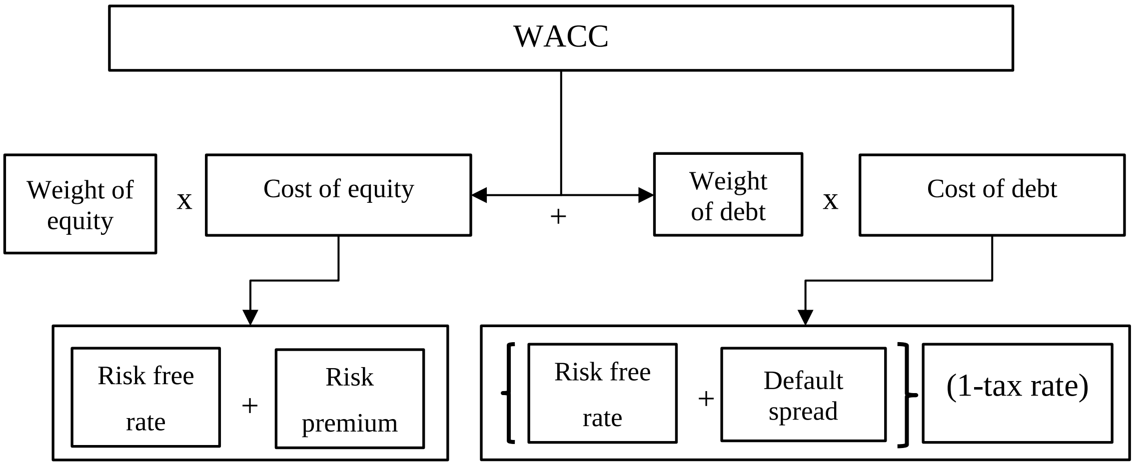
Domestic pipeline estimate	Regional pipeline estimate	Midstream
Material cost 287857.1427 26% Labour 498214.2855 45% Terrain 243571.4285 22% Misc. 77499.9999 7% Total cost **1,107,142**	Material cost 204699.6127 26% Labour 354287.7911 45% Terrain 173207.3646 22% Misc. 55111.4341 7% Total cost **787,306.20**	Material cost 122216.1694 26% Labour 211527.9855 45% Terrain 103413.6818 22% Misc. 32904.3533 7% Total cost **470,062.19**

(existing project) Option B:

Domestic pipeline estimate	Regional pipeline estimate	Midstream pipeline estimate
Material cost 26% 287,857.14 Tariff (40% of 26%) 29,937.14 Labour 45% 498,214.29 incremental labour (20% of 45%) 44,839.29 Terrain 22% 243,571.43 Misc. 7% 77,500.00 cost overrun 20% 221,428.57 average inflation 12.44% p.a 275,457.14 Total cost 1,678,805.00	Material cost 26% 204,699.61 Tariff (40% of 26%) 21,288.76 Labour 45% 354,287.79 incremental labour (20% of 45%) 31,885.90 Terrain 22% 173,207.36 Misc. 7% 55,111.43 cost overrun 20% 157,461.24 average inflation 12.44% p.a 195,881.78 Total cost 1,193,823.89	Material cost 26% 122,216.17 Tariff (40% of 26%) 12,710.48 Labour 45% 211,527.99 incremental labour (20% of 45%) 19,037.52 Terrain 22% 103,413.68 Misc. 7% 32,904.35 cost overrun 20% 94,012.44 average inflation 12.44% p.a 116,951.47 Total cost 712,774.10

Appendix 7

Weighted average cost of capital



Option A

WACC=

$$\frac{13701.55}{34253.80} * 10\% \quad + \quad \frac{20552.33}{34253.80} *13.5\% \quad * (0.7)$$

= 9.67%

Option B

WACC=

$$\frac{14050.26}{35125.65} * 10\% \quad + \quad \frac{20552.33}{35125.65} *13.5\% \quad * (0.8)$$

= 10.48%

Appendix 8

Capital expenditure breakdown

Domestic pipeline estimate $'000 (option A)

KM	Material $000	Labour$000	Terrain$000	Misc. $000	Total $000
32	9211.428567	15942.85714	7794.285711	2479.999999	35,428.57
40	11514.28571	19928.57142	9742.857139	3099.999999	44,285.71
50	14392.85714	24910.71428	12178.57142	3874.999998	55,357.14
75	21589.28571	37366.07141	18267.85714	5812.499998	83,035.71
100	28785.71427	49821.42855	24357.14285	7749.999997	110,714.29
125	35982.14284	62276.78569	30446.42856	9687.499996	138,392.86
150	43178.57141	74732.14283	36535.71427	11625.000000	166,071.43

Regional pipeline estimate $'000 (option A)

KM	Material $000	Labour $000	Terrain $000	Misc. $000	Total $000
32	6550.387605	11337.20932	5542.635666	1763.565894	25,193.80
40	8187.984506	14171.51165	6928.294582	2204.457367	31,492.25
50	10234.98063	17714.38956	8660.368228	2755.571709	39,365.31
75	15352.47095	26571.58433	12990.55234	4133.357563	59,047.97
100	20469.96127	35428.77911	17320.73646	5511.143418	78,730.62
125	25587.45158	44285.97389	21650.92057	6888.929272	98,413.28
150	30704.9419	53143.16867	25981.10468	8266.715126	118,095.93

Midstream pipeline estimate $'000 (option A)

KM	Material	Labour	Terrain	Misc.	Total
32	3910.917421	6768.895536	3309.237818	1052.939306	15,041.99
40	4888.646776	8461.11942	4136.547272	1316.174132	18,802.49
50	6110.80847	10576.39928	5170.68409	1645.217665	23,503.11
75	9166.212705	15864.59891	7756.026135	2467.826498	35,254.66
100	12221.61694	21152.79855	10341.36818	3290.43533	47,006.22
125	15277.02118	26440.99819	12926.71023	4113.044163	58,757.77
150	18332.42541	31729.19783	15512.05227	4935.652995	70,509.33

Domestic pipeline estimate $’000 (option B)

KM	Material	Tariff	Labour	Incremental labour	Terrain	Misc	Environmental permit	Cost overrun	inflation
32	9211.43	957.988571	15942.85714	1434.857142	7794.285711	2480	0.814332248	7085.714283	8814.628568
40	11514.29	1197.485714	19928.57142	1793.571428	9742.857139	3100	0.814332248	8857.142853	11018.28571
50	14392.86	1496.857142	24910.71428	2241.964285	12178.57142	3875	0.814332248	11071.42857	13772.85714
75	21589.29	2245.285713	37366.07141	3362.946427	18267.85714	5812.5	0.814332248	16607.14285	20659.28571
100	28785.71	2993.714284	49821.42855	4483.92857	24357.14285	7750	0.814332248	22142.85713	27545.71427
125	35982.14	3742.142856	62276.78569	5604.910712	30446.42856	9687.5	0.814332248	27678.57142	34432.14284
150	43178.57	4490.571427	74732.14283	6725.892854	36535.71427	11625	0.814332248	33214.2857	41318.57141

Regional pipeline estimate $’000 (option B)

	Material	Tariff	labour	incremental labour	Terrain	Misc	environmental permit	cost overrun	inflation
32	6,550.39	681.24	11,337.21	1,020.35	5,542.64	1,763.57	0.814332248	5,038.76	6,268.22
40	8,187.98	851.55	14,171.51	1,275.44	6,928.29	2,204.46	0.814332248	6,298.45	7,835.27
50	10,234.98	1,064.44	17,714.39	1,594.30	8,660.37	2,755.57	0.814332248	7,873.06	9,794.09
75	15,352.47	1,596.66	26,571.58	2,391.44	12,990.55	4,133.36	0.814332248	11,809.59	14,691.13
100	20,469.96	2,128.88	35,428.78	3,188.59	17,320.74	5,511.14	0.814332248	15,746.12	19,588.18
125	25,587.45	2,661.09	44,285.97	3,985.74	21,650.92	6,888.93	0.814332248	19,682.66	24,485.22
150	30,704.94	3,193.31	53,143.17	4,782.89	25,981.10	8,266.72	0.814332248	23,619.19	29,382.27

Midstream pipeline estimate $’000 (option B)

	Material	Tariff	labour	incremental labour	Terrain	Misc	environmental permit	cost overrun	inflation
32	3910.91742	406.7354118	6768.895536	609.2005982	3309.23782	1052.93931	0.814332248	3008.398016	3742.447132
40	4888.64678	508.4192647	8461.11942	761.5007478	4136.54727	1316.17413	0.814332248	3760.49752	4678.058915
50	6110.80847	635.5240809	10576.39928	951.8759348	5170.68409	1645.21767	0.814332248	4700.6219	5847.573644
75	9166.21271	953.2861213	15864.59891	1427.813902	7756.02614	2467.8265	0.814332248	7050.93285	8771.360465
100	12221.6169	1271.048162	21152.79855	1903.75187	10341.3682	3290.43533	0.814332248	9401.2438	11695.14729
125	15277.0212	1588.810202	26440.99819	2379.689837	12926.7102	4113.04416	0.814332248	11751.55475	14618.93411
150	18332.4254	1906.572243	31729.19783	2855.627804	15512.0523	4935.653	0.814332248	14101.8657	17542.72093

Appendix 9

Debt/equity financing

Domestic pipeline estimate $’000 (option A)

CAPEX	OPEX	Decommissioning	total exp	60% debt	40% equity
35,428.57	269.0267672	8790.55	44488.15	26692.89	17795.26
44,285.71	284.9269443	10158.55	54729.19	32837.51	21891.68
55,357.14	304.6521658	11868.55	67530.34	40518.21	27012.14
83,035.71	354.2652193	16143.55	99533.53	59720.12	39813.41
110,714.29	403.5782729	20418.55	131536.41	78921.85	52614.57
138,392.86	453.1913265	24693.55	163539.60	98123.76	65415.84
166,071.43	502.5043801	28968.55	195542.48	117325.49	78216.99

Regional pipeline estimate $’000 (option A)

CAPEX	OPEX	Decommissioning	total exp	60% debt	40% equity
25193.798	269.5299346	8790.55	34253.88	20552.33	13701.55
31492.248	285.5559036	10158.55	41936.35	25161.81	16774.54
39365.31	305.4383648	11868.55	51539.30	30923.58	20615.72
59047.965	355.4445179	16143.55	75546.96	45328.18	30218.78
78730.62	405.150671	20418.55	99554.32	59732.59	39821.73
98413.275	455.1568241	24693.55	123561.98	74137.19	49424.79
118095.93	504.8629772	28968.55	147569.34	88541.61	59027.74

Midstream pipeline estimate $’000 (option A)

CAPEX	OPEX	Decommissioning	total exp	60% debt	40% equity
25193.798	269.5299346	8790.55	34253.88	20552.33	13701.55
31492.248	285.5559036	10158.55	41936.35	25161.81	16774.54
39365.31	305.4383648	11868.55	51539.30	30923.58	20615.72
59047.965	355.4445179	16143.55	75546.96	45328.18	30218.78
78730.62	405.150671	20418.55	99554.32	59732.59	39821.73
98413.275	455.1568241	24693.55	123561.98	74137.19	49424.79
118095.93	504.8629772	28968.55	147569.34	88541.61	59027.74

Domestic pipeline estimate $’000 (option B)

CAPEX	OPEX	Decommissioning	Total Exp	60% debt	40% equity
26065.57474	269.5299346	8790.55	35125.65468	21075.39	14050.26
32581.76485	285.5559036	10158.55	43025.87075	25815.52	17210.35
40727.00247	305.4383648	11868.55	52900.99084	31740.59	21160.40
61090.09654	355.4445179	16143.55	77589.09106	46553.45	31035.64
81453.19062	405.150671	20418.55	102276.8913	61366.13	40910.76
101816.2847	455.1568241	24693.55	126964.9915	76178.99	50786.00
122179.3788	504.8629772	28968.55	151652.7917	90991.68	60661.12

Regional pipeline estimate $’000 (option B)

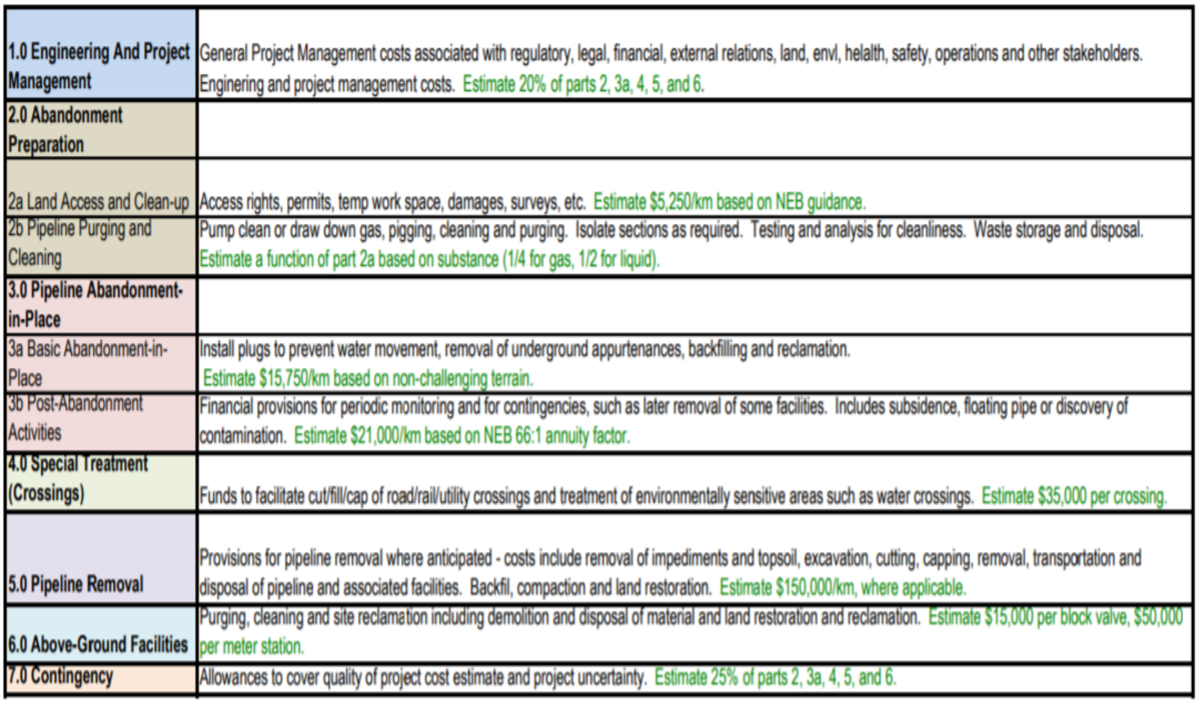
CAPEX	OPEX	Decommissioning	Total Exp	60% debt	40% equity
26065.57474	269.5299346	8790.55	35125.65468	21075.39	14050.26
32581.76485	285.5559036	10158.55	43025.87075	25815.52	17210.35
40727.00247	305.4383648	11868.55	52900.99084	31740.59	21160.40
61090.09654	355.4445179	16143.55	77589.09106	46553.45	31035.64
81453.19062	405.150671	20418.55	102276.8913	61366.13	40910.76
101816.2847	455.1568241	24693.55	126964.9915	76178.99	50786.00
122179.3788	504.8629772	28968.55	151652.7917	90991.68	60661.12

Midstream pipeline estimate $’000 (option B)

CAPEX	OPEX	Decommissioning	Total Exp	60% debt	40% equity
26065.57474	269.5299346	8790.55	35125.65468	21075.39	14050.26
32581.76485	285.5559036	10158.55	43025.87075	25815.52	17210.35
40727.00247	305.4383648	11868.55	52900.99084	31740.59	21160.40
61090.09654	355.4445179	16143.55	77589.09106	46553.45	31035.64
81453.19062	405.150671	20418.55	102276.8913	61366.13	40910.76
101816.2847	455.1568241	24693.55	126964.9915	76178.99	50786.00
122179.3788	504.8629772	28968.55	151652.7917	90991.68	60661.12

Appendix 10

Reference abandonment cost estimate guidance for pipeline



1.0 Engineering And Project Management	General Project Management costs associated with regulatory, legal, financial, external relations, land, envl, helalth, safety, operations and other stakeholders. Enginering and project management costs. Estimate 20% of parts 2, 3a, 4, 5, and 6.
2.0 Abandonment Preparation	
2a Land Access and Clean-up	Access rights, permits, temp work space, damages, surveys, etc. Estimate $5,250/km based on NEB guidance.
2b Pipeline Purging and Cleaning	Pump clean or draw down gas, pigging, cleaning and purging. Isolate sections as required. Testing and analysis for cleanliness. Waste storage and disposal. Estimate a function of part 2a based on substance (1/4 for gas, 1/2 for liquid).
3.0 Pipeline Abandonment-in-Place	
3a Basic Abandonment-in-Place	Install plugs to prevent water movement, removal of underground appurtenances, backfilling and reclamation. Estimate $15,750/km based on non-challenging terrain.
3b Post-Abandonment Activities	Financial provisions for periodic monitoring and for contingencies, such as later removal of some facilities. Includes subsidence, floating pipe or discovery of contamination. Estimate $21,000/km based on NEB 66:1 annuity factor.
4.0 Special Treatment (Crossings)	Funds to facilitate cut/fill/cap of road/rail/utility crossings and treatment of environmentally sensitive areas such as water crossings. Estimate $35,000 per crossing.
5.0 Pipeline Removal	Provisions for pipeline removal where anticipated - costs include removal of impediments and topsoil, excavation, cutting, capping, removal, transportation and disposal of pipeline and associated facilities. Backfil, compaction and land restoration. Estimate $150,000/km, where applicable.
6.0 Above-Ground Facilities	Purging, cleaning and site reclamation including demolition and disposal of material and land restoration and reclamation. Estimate $15,000 per block valve, $50,000 per meter station.
7.0 Contingency	Allowances to cover quality of project cost estimate and project uncertainty. Estimate 25% of parts 2, 3a, 4, 5, and 6.

Conversion:

1040 MMBtu/day = 1MMscfd

From Btu/ft^3 to Mj/m^3

1000 = 37.25

Therefore, 100Btu/ft^3 = 3.72589 Mj/m^3

Appendix 11

Computation of discounted cashflow and NPV (worst-case-scenario)

Years	discount factor	CAPEX (£)	DEVEX	OPEX	Decommission	Total cost	**Discounted COST**	Additional sales	**Discounted sales**	Revenues	Disc Revenues	**Discounted Cashflows**	Yearly NPV
0	1	15,041,990.08		0	0	15041990.08	15041990.08	0	0	0	0	-15041990.08	-15041990.08
1	0.911826388			269,326.90	0	269,326.90	245579.373	1497600	1365551.199	4942080	4506318.957	4260739.584	-10781250.5
2	0.831427362			269,326.90	0	269,326.90	223925.7527	1497600	1245145.618	4942080	4108980.539	3885054.786	-6896195.71
3	0.758117409			269,326.90	0	269,326.90	204181.4104	1425647.6	1080808.264	4704637.08	3566667.273	3362485.862	-3533709.848
4	0.691271459			269,326.90	0	269,326.90	186177.998	1274588.64	881086.7486	4206142.512	2907586.27	2721408.272	-812301.5754
5	0.630319558			269,326.90	0	269,326.90	169762.0114	1171561.04	738457.8364	3866151.432	2436910.86	2267148.849	1454847.273
6	0.574742006			269,326.90	0	269,326.90	154793.4818	1089847.2	626380.9656	3596495.76	2067057.186	1912263.705	3367110.978

7	0.524064927	269,326.90	0	269,326.90	141144.7814	1072567.6	562095.0612	3539473.08	1854913.702	1713768.921	5080879.899
8	0.47785623	269,326.90	0	269,326.90	128699.5362	356397.6	170306.8134	1176112.08	562012.4843	433312.9481	5514192.847
9	0.43572192	269,326.90	0	269,326.90	117351.6333	1226727.84	534512.2099	4048201.872	1763890.293	1646538.659	7160731.506
10	0.397302745	269,326.90	0	269,326.90	107004.316	1274055.12	506185.5961	4204381.896	1670412.467	1563408.151	8724139.657
11	0.362271127	269,326.90	0	269,326.90	97569.35894	1274055.12	461553.3838	4204381.896	1523126.167	1425556.808	10149696.46
12	0.330328373	269,326.90	0	269,326.90	88966.31617	1069216.72	353192.6196	3528415.176	1165535.645	1076569.328	11226265.79
13	0.301202127	269,326.90	0	269,326.90	81121.83475	1060010.64	319277.4598	3498035.112	1053615.617	972493.7825	12198759.58
14	0.274644048	269,326.90	0	269,326.90	73969.02959	1080050.4	296629.4138	3564166.32	978877.0655	904908.036	13103667.61
15	0.25042769	269,326.90	0	269,326.90	67446.91309	1114057.36	278990.8115	3676389.288	920669.6779	853222.7648	13956890.38
16	0.228346576	269,326.90	0	269,326.90	61499.87516	1081499.12	246956.6214	3568947.096	814956.8505	753456.9753	14710347.35
17	0.208212434	269,326.90	0	269,326.90	56077.20905	1153522.24	240177.6732	3806623.392	792586.3216	736509.1126	15446856.46
18	0.189853592	269,326.90	0	269,326.90	51132.67899	1242500.48	235893.1788	4100251.584	778447.4899	727314.8109	16174171.28
19	0.173113515	269,326.90	0	269,326.90	46624.12601	356397.6	61697.24119	1176112.08	203600.8959	156976.7699	16331148.05

20	0.157849471	269,326.90	0	269,326.90	42513.10842	1398836.4	220805.5857	4616160.12	728658.4327	686145.3243	17017293.37
21	0.143931313	269,326.90	0	269,326.90	38764.5741	1121865.68	161471.6003	3702156.744	532856.281	494091.7069	17511385.08
22	0.131240369	269,326.90	0	269,326.90	35346.5616	1144026	150142.3947	3775285.8	495469.9025	460123.3409	17971508.42
23	0.119668432	269,326.90	0	269,326.90	32229.9276	1205015.76	144202.3464	3976552.008	475867.7432	443637.8156	18415146.23
24	0.109116834	269,326.90	0	269,326.90	29388.09848	1408585.36	153700.375	4648331.688	507211.2374	477823.1389	18892969.37
25	0.099495609	269,326.90	0	269,326.90	26796.84369	1201418.4	119535.855	3964680.72	394468.3215	367671.4778	19260640.85
26	0.090722722	269,326.90	0	269,326.90	24434.0692	1348946.56	122380.1031	4451523.648	403854.3402	379420.271	19640061.12
27	0.082723371	269,326.90	0	269,326.90	22279.62907	356397.6	29482.41106	1176112.08	97291.95651	75012.32744	19715073.45
28	0.075429353	269,326.90	0	269,326.90	20315.15371	1362889.84	102801.8989	4497536.472	339246.2664	318931.1127	20034004.56
29	0.068778475	269,326.90	0	269,326.90	18523.89323	1317226.56	90596.83345	4346847.648	298969.5504	280445.6572	20314450.22
30	0.062714028	269,326.90	8,790,550.00	9,059,876.90	568181.3739	1309168.64	82103.23881	4320256.512	270940.6881	-297240.6859	20017209.53
										20017209.53	
		8,079,806.95			**18,203,790.95**		11,154,756.87	113,824,521.10	**38,221,000.48**		
				LCOE	1.631930768	$/mmscfd					
				NPV	20,017,209.53	$					

List of References

[1] Chopra S. Meindl P. Supply chain management : Supply, Planning and Strategy. 5th ed. Prentice Hall; 2012.

[2] Dani S-V. Designing and managing supply chain. Mcgraw Hill College, USA; 2008.

[3] Shapiro J. Modeling the supply chain. Cengage Learning; 2006.

[4] Asif M, Muneer T. Energy supply, its demand and security issues for developed and emerging economies. Renew Sustain Energy Rev 2007;11:1388–413. doi:10.1016/j.rser.2005.12.004.

[5] Dincer I. Renewable energy and sustainable development: a crucial review. Renew Sustain Energy Rev 2000;4:157–75. doi:10.1016/S1364-0321(99)00011-8.

[6] Nel WP, Cooper CJ. Implications of fossil fuel constraints on economic growth and global warming. Energy Policy 2009;37:166–80. doi:10.1016/j.enpol.2008.08.013.

[7] British Petroleum. BP statistical review of world energy. 68th Ed 2019. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

[8] GOV.UK. Natural gas 2019. https://www.gov.uk/government/statistics/natural-gas-chapter-4-digest-of-united-kingdom-energy-statistics-dukes (accessed February 18, 2020).

[9] IPPC. Global warming of 1.5 ^{o}C. Special Report. 2018. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_High_Res.pdf(accessed December 15, 2019)

[10] British Petroleum. BP energy outlook 2019 edition. 2019.

[11] Pollitt M. The arguments for and against ownership unbundling of energy transmission networks. Energy Policy 2008;36:704–13. doi:10.1016/j.enpol.2007.10.011.

[12] Carvalho H, Barroso AP, Machado VH, Azevedo S, Cruz-Machado V. Supply chain redesign for resilience using simulation. Comput Ind Eng 2012;62:329–41. doi:10.1016/J.CIE.2011.10.003.

[13] Lee YH, Kim SH. Production-distribution planning in supply chain considering capacity constraints. Comput Ind Eng 2002;43:169–90. doi:10.1016/S0360-8352(02)00063-3.

[14] Kleindorfer PR, Saad GH. Managing disruption risks in supply chains. Prod Oper Manag 2005;14:53–68.

[15] Mokhatab S. Handbook of natural gas transmission and processing. Fourth. Gulf Professional Publishing; 2019.

[16] Hamedi M, Zanjirani, FRH, Mohammad ME, Gholam R. A distribution planning model for natural gas supply chain: A case study. Energy Policy 2009;37:799–812. doi:10.1016/j.enpol.2008.10.030.

[17] MacKinnon MA, Brouwer J, Samuelsen S. The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration. Prog Energy Combust Sci 2018;64:62–92. doi:10.1016/J.PECS.2017.10.002.

[18] Leicher J, Giese A, Görner K. The impact of natural gas quality on large-scale combustion processes in thermal processing industries and power generation. J Int Flame Res Found 2017.

[19] Emenike SN, Falcone G. A review on energy supply chain resilience through optimization. Renew Suatainable Energy Rev 2020;134. doi:https://doi-org.ezproxy.lib.gla.ac.uk/10.1016/j.rser.2020.110088.

[20] Lee A, Zinaman O, Logan J, Bazilian M, Arent D, Newmark RL. Interactions, complementarities and tensions at the nexus of natural gas and renewable energy. Electr J 2012;25:38–48. doi:10.1016/j.tej.2012.10.021.

[21] World Energy Council. World energy resources 2016. https://www.worldenergy.org/wp.../World-Energy-Resources-Full-report-2016.10.03.pd...

[22] Ríos-Mercado RZ, Borraz-Sánchez C. Optimization problems in natural gas transportation systems: A state-of-the-art review. Appl Energy 2015;147:536–55. doi:10.1016/J.APENERGY.2015.03.017.

[23] Economides MJ, Wood DA. The state of natural gas. J Nat Gas Sci Eng 2009;1:1–13. doi:10.1016/j.jngse.2009.03.005.

[24] Speight JG. Natural gas : a basic handbook. 2nd ed. Boston: Gulf Professional Publishing; 2019. doi:https://doi.org/10.1016/B978-0-12-809570-6.00001-1.

[25] Speight JG. History and use. Nat. Gas. second, Gulf Professional Publishing; 2019, p. 3–24. doi:10.1016/b978-0-12-809570-6.00001-1.

[26] Department for Petroleum Resources. Harnessing nigeria’s flare gas for sustainable value & wealth creation 2020. https://ngfcp.dpr.gov.ng/about-us/historical-background/ (accessed February 22, 2020).

[27] Faramawy S, Zaki T, Sakr AAE. Natural gas origin, composition, and processing: A review. J Nat Gas Sci Eng 2016. doi:10.1016/j.jngse.2016.06.030.

[28] Tabkhi F, Azzaro-Pantel C, Pibouleau L, Domenech S. A mathematical framework

for modelling and evaluating natural gas pipeline networks under hydrogen injection. Int J Hydrogen Energy 2008;33:6222–31. doi:10.1016/J.IJHYDENE.2008.07.103.

[29] Gao J, You F. Sustainable design and operation of shale gas supply chain networks with life cycle economic and environmental optimisation. Chem Eng Trans Vol 2015;45:493–8. doi:10.3303/CET1545083.

[30] Mokhatab S, Poe AW. Handbook of natural gas transmission and processing. 2nd ed. Elsevier Inc; 2012.

[31] Harrison MR, Shires TM, Wessels JK, Cowgill R. Methane emissions from the natural gas industry. Volume 1: executive summary. EPA-600/R-96-080a. U.S. Environmental Protection Agency, Office of Research and Development, Washington, 1996;1.

[32] Touretzky CR, McGuffin DL, Ziesmer JC, Baldea M. The effect of distributed electricity generation using natural gas on the electric and natural gas grids. Appl Energy 2016;177:500–14. doi:10.1016/j.apenergy.2016.05.098.

[33] IEA. Global energy & co2 status report: emissions. IeaOrg 2019.

[34] Exxonmobil. 6 Charts that explain why natural gas will be a critical fuel for the future 2020. https://energyfactor.exxonmobil.eu/news/6-charts-explain-natural-gas-will-fuel-future/?gclid=Cj0KCQiAnL7yBRD3ARIsAJp_oLb8SQVl942ED5n66lSOJumdo3WF5D9OeL4nxLZRYnc9-gZNN6XgotIaApF7EALw_wcB (accessed February 22, 2020).

[35] Cheremisinoff NP. Pollution control handbook for oil and gas engineering. Wiley; 2016.

[36] Environmental PA. Redesign blowdown systems and alter esd practices. U.S:

Natural Gas EPA Pollution Preventer 2011. https://www.epa.gov/natural-gas-star-program/redesign-blowdown-systems-and-alter-emergency-shutdown-practices. (accessed July 4, 2018).

[37] Carvalho H, Machado CV. Designing principles to create resilient supply chains. In Proceedings of the 2007 industrial engineering research conference, Nashville, TN: 2007, p. 186–191.

[38] Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM, et al. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthquake Spectra; 2003.

[39] Christopher M, Peck H. Building the Resilient Supply Chain. Internaltional J Logist Manag 2004;15:1–14.

[40] Hoggett R. Technology scale and supply chains in a secure, affordable and low carbon energy transition. Appl Energy 2014;123:296–306. doi:10.1016/J.APENERGY.2013.12.006.

[41] Cimellaro GP, Villa O, Bruneau M. Resilience-Based Design of Natural Gas Distribution Networks. J Infrastruct Syst 2015;21.

[42] Moslehi S, Reddy TA. Sustainability of integrated energy systems: A performance-based resilience assessment methodology. Appl Energy 2018;228:487–98. doi:10.1016/J.APENERGY.2018.06.075.

[43] Bocchini P, Frangopol DM, Ummenhofer T, Zinke T. resilience and sustainability of civil infrastructure: toward a unified approach. J Infrastruct Syst 2014;20.

[44] Hussain A, Bui V-H, Kim H-M. Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience. Appl Energy 2019;240:56–72. doi:10.1016/J.APENERGY.2019.02.055.

[45] Schmitt AJ, Singh M. A quantitative analysis of disruption risk in a multi-echelon supply chain. Int J Prod Econ 2012;139:22–32. doi:10.1016/J.IJPE.2012.01.004.

[46] Todini E. Looped water distribution networks design using a resilience index based heuristic approach. Urban Water 2000;2:115–22. doi:10.1016/S1462-0758(00)00049-2.

[47] Burke GJ, Carrillo JE, Vakharia AJ. Single versus multiple supplier sourcing strategies. Eur J Oper Res 2007;182:95–112. doi:10.1016/J.EJOR.2006.07.007.

[48] Sayed AR, Wang C, Bi T. Resilient operational strategies for power systems considering the interactions with natural gas systems. Appl Energy 2019;241:548–66. doi:10.1016/J.APENERGY.2019.03.053.

[49] Venkata SSM, Hatziargyriou N. Grid resilience: elasticity is needed when facing catastrophes. IEEE Power Energy Mag 2015:16–23. doi:https://doi.org/10.1109/MPE.2015.2401492.

[50] Almoghathawi Y, Barker K, Albert LA. Resilience-driven restoration model for interdependent infrastructure networks. Reliab Eng Syst Saf 2019;185:12–23. doi:10.1016/J.RESS.2018.12.006.

[51] Lin Y, Bie Z. Study on the Resilience of the Integrated Energy System. Energy Procedia 2016;103:171–6. doi:10.1016/J.EGYPRO.2016.11.268.

[52] Jufri FH, Widiputra V, Jung J. State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies. Appl Energy 2019;239:1049–65. doi:10.1016/J.APENERGY.2019.02.017.

[53] Papageorgiou LG. Supply chain optimisation for the process industries: Advances and opportunities. Comput Chem Eng 2009;33:1931–8. doi:10.1016/j.compchemeng.2009.06.014.

[54] Garcia DJ, You F. Supply chain design and optimization: Challenges and opportunities. Comput Chem Eng 2015;81:153–70. doi:10.1016/J.COMPCHEMENG.2015.03.015.

[55] Shah N. Process industry supply chains: Advances and challenges. Comput Chem Eng 2005;29:1225–35. doi:10.1016/J.COMPCHEMENG.2005.02.023.

[56] Paul S, Sarker R, Essam D. Managing risk and disruption in production-inventory and supply chain systems: A review. J Ind Manag Optim 2016;12:1009–29.

[57] Bahadur A, Lovell E, Wilkinson E, Tanner T. Resilience in the SDGs; Developing an indicator for Target 1.5 that is fit for purpose. UK: Overseas Dev InstitutE: 2015.

[58] IPCC. Appendix I: Glossary. In: Climate change 2007: Impacts, Adaptation and vulnerability. contribution of working group ii to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, UK, and New York, NY: Cambridge University Press; 2007.

[59] Carvalho R, Buzna L, Bono F, Masera M, Arrowsmith D, Helbing D. Resilience of natural gas networks during conflicts, crises and disruptions. PLoS One 2014.

[60] O'Brien K, Pelling M, Patwardhan A, Hallegatte S, Maskrey A, Oki T et al. Toward a sustainable and resilient future. In: Managing the risks of extreme events and disasters to advance climate change adaptation. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G.-K, Allen SK, Tignor M, Midgley PM. editors. UK, and New York, NY, USA: Cambridge University Press, Cambridge; 2012.

[61] Ganeshan R, Harrison TP. An introduction to supply chain management 2002. http://mason.wm.edu/faculty/ganeshan_r/documents/intro_supply_chain.pdf.

[62] Hugo M. Essentials of supply chain Management. John Wiley & Sons ; 2003.

[63] Chopra S, Meindl P. Supply chain management : strategy, planning and operation. 3rd ed. 2007.

[64] Schary PB, Skjott-Larsen T. Managing the global supply chain. 2nd ed. Copenhagen Business School Press; 2001.

[65] Mula J, Peidro D, Díaz-Madroñero M, Vicens E. Mathematical programming models for supply chain production and transport planning. Eur J Oper Res 2010;204:377–90. doi:10.1016/J.EJOR.2009.09.008.

[66] Midthun KT, Nørstebø VS, Tomasgard A, Werner AS. Natural Gas Networks. Encycl Energy, Nat Resour Environ Econ 2013:161–7. doi:10.1016/B978-0-12-375067-9.00120-0.

[67] Azadeh A, Raoofi Z. An optimization model for natural gas supply chain through a cost approach under uncertainty. World Acad Sci Eng Technol 2014;8:2737–40.

[68] Menon SE. GAS PIPELINE HYDRAULICS. First. New York: Taylor & Francis Group, LLC; 2005.

[69] Bopp AE, Kannan VR, Palocsay SW, Stevens SP. An optimization model for planning natural gas purchases, transportation, storage and deliverability. Omega 1996;24:511–22. doi:10.1016/0305-0483(96)00025-4.

[70] Fügenschuh A, Geißler B, Gollmer R, Morsi A, Pfetsch M, Rövekamp J et al. Physical and technical fundamentals of gas networks. In: Koch,T., Hiller,B., Pfetsch, M, E., Schewe L, editor. Eval. Gas Netw. Capacit., SIAM; 2015, p. 17–43.

[71] Petroleum Economist. Nigeria secures $2.5bn gas pipeline finance 2020.

[72] Tomasgard A, Rømo F, Midthun K, Fodstad M. Optimization models for the natural gas value chain. In: Hasle G., Lie KA. QE (eds), editor. Geom. Model. Numer. Simulation, Optim., Springer, Berlin, Heidelberg; 2007.

doi:https://doi.org/10.1007/978-3-540-68783-2_16.

[73] Contesse L, Ferrer JC, Muturana S. A Mixed-integer programming model for gas purchase and transportation. Ann Oper Res 2005:39–63.

[74] Su H, Zhang J, Zio E, Yang N, Li X, Zhang Z. An integrated systemic method for supply reliability assessment of natural gas pipeline networks. Appl Energy 2018;209:489–501. doi:10.1016/J.APENERGY.2017.10.108.

[75] Azadeh A, Raoofi Z, Zarrin M. A multi-objective fuzzy linear programming model for optimization of natural gas supply chain through a greenhouse gas reduction approach. J Nat Gas Sci Eng 2015;26:702–10. doi:10.1016/J.JNGSE.2015.05.039.

[76] Chiang W-C, Russell RA. Integrating purchasing and routing in a propane gas supply chain. Eur J Oper Res 2004;154:710–29. doi:10.1016/S0377-2217(02)00818-4.

[77] Kabirian A, Hemmati MR. A Strategic planning model for natural gas transmission network. Enery Policy 2007;35:5656–70.

[78] Collette Y, Siarry P. Multiobjective optimization: principles and case studies. New York: Springer; 2003.

[79] Chopra S. Meindl P. Supply chain management strategy, planning, and operation. 6th ed. New York: Pearson; 2016.

[80] Xiang L, Tomasgard A, Barton PI. Natural gas production network infrastructure development. Optim Eng 2017;18.1:35–62

[81] Hellemo L, Midthun K, Tomasgard A, Werner A. Natural gas infrastructure design with an operational perspective. Energy Procedia 2012;26:67–73. doi:10.1016/J.EGYPRO.2012.06.011.

[82] Woldeyohannes AD, Majid MAA. Simulation model for natural gas transmission pipeline network system. Simul Model Pract Theory 2011;19:196–212. doi:10.1016/J.SIMPAT.2010.06.006.

[83] Sedliak A, Zacik T. Optimization of the gas transport. Math Publ 2016:103–20.

[84] Sukharev MG, Kosova KO. A parameter identification method for natural gas supply systems under unsteady gas flow. Autom Remote Control 2017;78:882–90. doi:10.1134/S0005117917050101.

[85] Brundtland GH. Our common future: Brundtland-report. Oxford University Press, Oxford.: 1987.

[86] Carter CR, Rogers DS. A framework of sustainable supply chain management: moving toward new theory. Int J Phys Distrib Logist Manag 2008;38:360–87. doi:10.1108/09600030810882816.

[87] Seuring S. A review of modeling approaches for sustainable supply chain management. Decis Suppport Syst 2013;54:1513–20.

[88] Hepbasli A. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew Sustain Energy Rev 2008;12:593–661. doi:10.1016/J.RSER.2006.10.001.

[89] Türkay M, Oruç C, Fujita K, Asakura T. Multi-company collaborative supply chain management with economical and environmental considerations. Comput. Chem. Eng., vol. 28, 2004, p. 985–92. doi:10.1016/j.compchemeng.2003.09.005.

[90] Zarei J, Amin-Naseri MR, Fakehi Khorasani AH, Kashan AH. A sustainable multi-objective framework for designing and planning the supply chain of natural gas components. J Clean Prod 2020;259:120649. doi:10.1016/j.jclepro.2020.120649.

[91] Nocedal J, Wright SJ. Numerical optimization. second. New York: Springer

Science+Business Media, LLC; 2006.

[92] Fahimnia B, Farahani RZ, Marian R, Luong L. A review and critique on integrated production–distribution planning models and techniques. J Manuf Syst 2013;32:1–19. doi:10.1016/J.JMSY.2012.07.005.

[93] Byrne MD, Bakir MA. Production planning using a hybrid simulation – analytical approach. Int J Prod Econ 1999;59:305–11.

[94] Lee YH, Kim SH. Production–distribution planning in supply chain considering capacity constraints. Comput Ind Eng 2002;43:169–90. doi:10.1016/S0360-8352(02)00063-3.

[95] Daghigh R, Pishvaee MS. Integrated optimization of gas supply chain network design problem and Liquefied Natural gas contract selection. Int. Conf. Ind. Eng., 2017.

[96] Kanyalkar AP, Adil GK. An integrated aggregate and detailed planning in a multi-site production environment using linear programming. Int J Prod Res 2005;43:4431–54. doi:10.1080/00207540500142332.

[97] Luenberger DG, Ye Y. Linear and nonlinear programming. 4th ed. Stanford: Springer; 2016.

[98] Shi Y, Peng Y, Yong S. Multiple criteria & multiple constraint levels linear programming. 2001.

[99] Bazaraa MS, Jarvis JJ, Sherali HD. Linear programming and network flows. fourth. New York: John Wiley & Sons, Inc.; 2010.

[100] Mula J, Peidro D, Diaz-Madronero M, Vicens E. Mathematical programming models for supply chain production and transport planning. Eur J Oper Res 2010;204:377–90.

[101] Chen M, Wang W. A linear programming model for integrated steel production and distribution planning. Int J Oper Prod Manag 1997;17:592–610. doi:10.1108/01443579710167276.

[102] Jung H, Jeong B, Lee C-G. An order quantity negotiation model for distributor-driven supply chains. Int J Prod Econ 2008;111:147–58. doi:10.1016/j.ijpe.2006.12.054.

[103] Martin CH, Dent DC, Eckhart CJ. Integrated production, distribution, and inventory planning at Libbey-Owens-Ford 1993:78–86.

[104] Oh H-C, Karimi IA. Global multiproduct production-distribution planning with duty drawbacks. AIChE J 2006;52:595–610. doi:10.1002/aic.10669.

[105] Ryu J-H, Dua V, Pistikopoulos EN. A bilevel programming framework for enterprise-wide process networks under uncertainty. Comput Chem Eng 2004;28:1121–9. doi:10.1016/j.compchemeng.2003.09.021.

[106] Chern C-C, Hsieh J-S. A heuristic algorithm for master planning that satisfies multiple objectives. Comput Oper Res 2007;34:3491–513. doi:10.1016/j.cor.2006.02.022.

[107] Selim H, Araz C, Ozkarahan I. Collaborative production-distribution planning in supply chain: A fuzzy goal programming approach. Transp Res Part E Logist Transp Rev 2008;44:396–419. doi:10.1016/j.tre.2006.11.001.

[108] Torabi SA, Hassini E. An interactive possibilistic programming approach for multiple objective supply chain master planning. Fuzzy Sets Syst 2008;159:193–214. doi:10.1016/j.fss.2007.08.010.

[109] Vasconcelos CD, Lourenço SR, Gracias AC, Cassiano DA. Network flows modeling applied to the natural gas pipeline in Brazil. J Nat Gas Sci Eng 2013;14:211–24. doi:10.1016/J.JNGSE.2013.07.001.

[110] Dantzig. B. G. Linear Programming and extensions. California: 1963.

[111] Barbarosoğlu G, Özgür D. Hierarchical design of an integrated production and 2-echelon distribution system. Eur J Oper Res 1999;118:464–84. doi:10.1016/S0377-2217(98)00317-8.

[112] Kallrath J. Combined strategic and operational planning - An MILP success story in chemical industry. OR Spectr 2002;24:315–41. doi:10.1007/s00291-002-0102-6.

[113] Timpe CH, Kallrath J. Optimal planning in large multi-site production networks. Eur J Oper Res 2000;126:422–35. doi:10.1016/S0377-2217(99)00301-X.

[114] Dhaenens-Flipo C, Finke G. An integrated model for an industrial production-distribution problem. IIE Trans (Institute Ind Eng 2001;33:705–15. doi:10.1023/A:1010937614432.

[115] McDonald CM, Karimi IA. Planning and scheduling of parallel semicontinuous processes. 1. Production planning. Ind Eng Chem Res 1997;36:2691–700. doi:10.1021/ie960901+.

[116] Gen M, Syarif A. Hybrid genetic algorithm for multi-time period production/distribution planning. Comput Ind Eng 2005;48:799–809. doi:10.1016/j.cie.2004.12.012.

[117] Incekara CO, Ogulata SN. Turkey’s energy planning considering global environmental concerns. Ecol Eng 2017;102:589–95. doi:10.1016/j.ecoleng.2017.02.033.

[118] Chinneck CJ. Introduction to nonlinear programming. Pract. Optim. A Gentle Introd., 2015.

[119] Lababidi HMS, Ahmed MA, Alatiqi IM, Al-Enzi AF. Optimizing the supply chain of a petrochemical company under uncertain operating and economic conditions.

Ind Eng Chem Res 2004;43:63–73.

[120] Sakawa M, Nishizaki I, Uemura Y. Fuzzy programming and profit and cost allocation for a production and transportation problem. Eur J Oper Res 2001;131:1–15. doi:10.1016/S0377-2217(00)00104-1.

[121] Aliev RA, Fazlollahi B, Guirimov BG, Aliev RR. Fuzzy-genetic approach to aggregate production-distribution planning in supply chain management. Inf Sci (Ny) 2007;177:4241–55. doi:10.1016/j.ins.2007.04.012.

[122] Liang T-F, Cheng H-W. Application of fuzzy sets to manufacturing/distribution planning decisions with multi-product and multi-time period in supply chains. Expert Syst Appl 2009;36:3367–77. doi:10.1016/J.ESWA.2008.01.002.

[123] Sabri EH, Beamon BM. A multi-objective approach to simultaneous strategic and operational planning in supply chain design. Omega 2000;28:581–98. doi:10.1016/S0305-0483(99)00080-8.

[124] Lee JH. Energy supply planning and supply chain optimization under uncertainty. J Process Control 2014;24:323–31. doi:10.1016/j.jprocont.2013.09.025.

[125] Ishii K, Takahashi K, Muramatsu R. Integrated production, inventory and distribution systems. Int J Prod Res 1988;26:473–82. doi:10.1080/00207548808947877.

[126] Mirzapour Al-e-hashem SMJ, Malekly H, Aryanezhad MB. A multi-objective robust optimization model for multi-product multi-site aggregate production planning in a supply chain under uncertainty. Int J Prod Econ 2011;134:28–42. doi:10.1016/J.IJPE.2011.01.027.

[127] Bossel H. Modelling and simulation. First. Kassel: Verlag Vieweg; 1994.

[128] Wets RJB. Optimization. First Edit. New York: Elsevier Science Publishing

Company INC; 1991.

[129] Goh M, Lim JYS, Meng F. A stochastic model for risk management in global supply chain networks. Eur J Oper Res 2007;182:164–73. doi:10.1016/J.EJOR.2006.08.028.

[130] Kbah Z, Erdil NO, Aqlan F. Analysis of oil and gas supply chain using continuous-time discrete-event simulation. Proc. 2016 Ind. Syst. Eng. Res. Conf., 2016.

[131] Ke S, Ti H. Transient analysis of isothermal gas flow in pipeline network. Chem Eng J 2000;76:169–77. doi:10.1016/S1385-8947(99)00122-9.

[132] National Energy Technology Laboratory. Fuel cell handbook (Seventh Edition) 2004:0880. https://netl.doe.gov/sites/default/files/netl-file/FCHandbook7.pdf.

[133] Azadeh A, Shabanpour N, Soltanpour Gharibdousti M, Nasirian B. Optimization of supply chain based on macro ergonomics criteria: A case study in gas transmission unit. J Loss Prev Process Ind 2016;43:332–51. doi:10.1016/j.jlp.2016.05.024.

[134] Kazemi Y, Szmerekovsky J. Modeling downstream petroleum supply chain: The importance of multi-mode transportation to strategic planning. Transp Res Part E Logist Transp Rev 2015;83:111–25. doi:10.1016/J.TRE.2015.09.004.

[135] Liu SPL. Multiobjective optimisation of production, distribution and capacity planning of global supply chains in the process industry. Omega 2013;41:369–82. doi:10.1016/J.OMEGA.2012.03.007.

[136] Rosenthal RE. GAMS —A User’s Guide. Washington, DC, USA: GAMS Development Corporation; 2017.

[137] Voudouris VT. Mathematical programming techniques to debottleneck the supply chain of fine chemical industries. Comput Chem Eng 1996;20.

[138] Rangaiah GP. Multi-objective optimization: techniques and applications in chemical engineering. Singapore: World scientific publishing co.pte.ltd; 2009.

[139] Poe WA, Mokhatab S. Modeling, control, and optimization of natural gas processing plants. Gulf Professional Publishing; 2017.

[140] ISO. ISO 14044: Environmental management – life cycle assessment – requirements and guidelines. Geneva; 2006. https://scholar.google.com/scholar?q=ISO. ISO 14044: environmental management life cycle assessment requirements and guidelines. Geneva; 2006. (accessed March 26, 2020).

[141] Shahpari A, Aminsharei F, Ghashang M. Application of PHAST software in methane emission factor for startup process of gas compressors (Case study: Iran gas transmission operation district 2). J Air Pollut Heal 2019;4:27–32.

[142] World Gas Conference 2018 EDITION. Wholes. gas price Surv. 2018 Ed. A Glob. Rev. PRICE Form. Mech. 2005 TO 2017 JUNE 2018, Bercelonia: International Gas Union (IGU); 2018.

[143] Santley D, Schlotterer R, Eberhard A. Harnessing African natural gas : a new opportunity for Africa’s energy agenda? Washington, DC: 2014.

[144] Kevin P, Julio M, Andrew G. North America midstream infrastructure through 2035 Significant Development Continues. Washington, DC: 2018.

[145] Ulvestad M, Overland I. Natural gas and CO2 price variation: impact on the relative cost-efficiency of LNG and pipelines. Int J Environ Stud 2012;69:407–26. doi:DOI: 10.1080/00207233.2012.677581.

[146] Ioannou A, Angus A, Brennan F. A lifecycle techno-economic model of offshore wind energy for different entry and exit instances. Appl Energy 2018;221:406–24. doi:10.1016/J.APENERGY.2018.03.143.

[147] Reuters. UPDATE 1- Nigerian bond yeilds drop after suprise central bank rate cut 2019. https://www.reuters.com/article/nigeria-bonds/update-1-nigerian-bond-yields-drop-after-surprise-central-bank-rate-cut-idUSL8N21E396 (accessed March 27, 2019).

[148] Deloitte. Corporate tax rates 2020 2020. https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Tax/dttl-tax-corporate-tax-rates.pdf (accessed June 18, 2020).

[149] World Government Bonds. Nigeria Government Bonds - Yields Curve 2020. http://www.worldgovernmentbonds.com/country/nigeria/ (accessed June 22, 2020).

[150] Almansoori A, Shah N. Design and Operation of a Future Hydrogen Supply Chain: Snapshot Model. Chem Eng Res Des 2006;84:423–38. doi:10.1205/CHERD.05193.

[151] Dodds PE, McDowall W. The future of the UK gas network. Energy Policy 2013;60:305–16. doi:10.1016/J.ENPOL.2013.05.030.

[152] UNFCCC. The Paris Agreement. Paris: 2015.

List of conference paper presentations/Journal publications and submission

1. 2019: Natural gas supply chain resilience through optimization. 10th International Conference and Expo on Oil and Gas 2019. London, United Kingdom

2. 2020: A review on energy supply chain resilience through optimization. Renew Sustainable Energy Rev 2020;134. doi:https://doi-org.ezproxy.lib.gla.ac.uk/10.1016/j.rser.2020.110088

3. 2020/2021: Special issue publication- Optimization of gas loss and CO_2 emission during disruption on a natural gas network. Paper ID APEN-MIT-2020_001.Applied Energy Symposium. MIT A+B August 12-13, 2020. Cambridge, USA. https://www.youtube.com/watch?v=WMI8w8a37PM

4. 2021: Research paper submission to Journal- An integrated MILP model for resilient and sustainable natural gas supply chain