
MODELLING AND OPTIMIZATION OF UNDERGROUND OIL PIPELINE NETWORK DESIGN

A thesis submitted to the

UPES

For the Award of

Doctor of Philosophy

In

Petroleum Engineering

by

Bharat Sharma

June 2024

SUPERVISOR

Dr. Sunil Kumar Khare



DEPARTMENT OF PETROLEUM ENGINEERING AND EARTH SCIENCES

ENERGY CLUSTER, SCHOOL OF ADVANCE ENGINEERING

UPES, DEHRADUN

MODELLING AND OPTIMIZATION OF UNDERGROUND OIL PIPELINE NETWORK DESIGN

A thesis submitted to the

UPES

For the Award of

Doctor of Philosophy

In

Petroleum Engineering

by

Bharat Sharma

(SAP ID: 500066156)

June 2024

SUPERVISOR

Dr. Sunil Kumar Khare

Professor, Department of Petroleum Engineering and Earth Sciences,
Energy Cluster, School of Advance Engineering, UPES, Dehradun



DEPARTMENT OF PETROLEUM ENGINEERING AND EARTH SCIENCES
ENERGY CLUSTER, SCHOOL OF ADVANCE ENGINEERING
UPES, DEHRADUN

Certificate

It is certified that the work contained in this thesis entitled “**MODELLING AND OPTIMIZATION OF UNDERGROUND OIL PIPELINE NETWORK DESIGN**” by **Bharat Sharma** has been carried out under my supervision and that it has not been submitted elsewhere for a degree.



Prof. Sunil Kumar Khare

Professor

Department of Petroleum Engineering and Earth Sciences

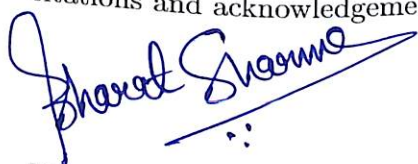
Energy Cluster, School of Advance Engineering

UPES, Dehradun

Declaration

This is to certify that the thesis titled “MODELLING AND OPTIMIZATION OF UNDERGROUND OIL PIPELINE NETWORK DESIGN” has been authored by me. It presents the research conducted by me under the supervision of **Prof. Sunil Kumar Khare**.

To the best of my knowledge, it is an original work, both in terms of research content and narrative, and has not been submitted elsewhere, in part or in full, for a degree. Further, due credit has been attributed to the relevant state-of-the-art collaborations with appropriate citations and acknowledgements, in line with established norms and practices.



Bharat Sharma

Roll No. 500066156

Department of Petroleum Engineering and Earth Sciences

UPES, Dehradun

Abstract

Name of the student: **Bharat Sharma**

Roll No: **500066156**

Degree for which submitted: **Doctor of Philosophy (Petroleum Engineering)**

Department: **Department of Petroleum Engineering and Earth Sciences**

Thesis title: **MODELLING AND OPTIMIZATION OF UNDERGROUND OIL
PIPELINE NETWORK DESIGN**

Thesis supervisors: **Prof. Sunil Kumar Khare**

Month and year of thesis submission: **June 2024**

Petroleum pipeline projects are essential for the efficient and cost-effective transport of large volumes of oil over long distances with minimal energy consumption. However, these projects require substantial capital investments and even minor improvements in pipeline network design can lead to significant savings in both capital and operating costs. Hence, optimising Pipeline Network Configuration (PNC) is crucial and demands meticulous attention. Currently, pipeline design engineers rely on iterative trial-and-error methods to select PNCs based on their experience and judgment, considering factors like economic viability, topological complexities, and technical constraints. This labour-intensive, and time-consuming approach can result in sub-optimal solutions due to the vast number of possible design variations. With the prospect of investing over INR 1 lakh crores in upcoming pipeline projects in India itself, it is crucial to address the potential risk of sub-optimal pipeline networks.

To tackle these challenges, this study proposes system-based PNC design optimization frameworks that encompass all critical Technical-Environment-Commercial (TEC) factors. Unlike existing literature, the proposed approach comprehensively considers TEC factors such as terrain profile, thermal impact, pipe thickness, dynamic pump efficiency, cost escalation, tariffs,

project phasing, depreciation factor, and carbon emissions. For the first time, the study suggests using all standard diameters and thicknesses specified in API 5L. It also incorporates the construction of Sectionalising Valve (SV) and Intermediate Pigging Station (IPS) in modelling, as they impact TEC aspects and serve as additional potential nodes for the construction of Intermediate Pigging and Pumping Station (IPPS). These novel provisions in decision variables expand the search space of optimization solutions.

Additionally, this study considers product linefill cost and tankage cost, which significantly impact cost by 22.77%, potentially leading to erroneous decision-making in both PNC design and operational phases if neglected. This study introduces a novel tariff-based objective function that considers complete cash-flow statements, including depreciation, income tax, Capital Expenditure (CAPEX), Operating Expenditure (OPEX), and generated revenue. Moreover, in response to increasing climate change concerns, the study extends its scope to include carbon emissions generated from pipeline project construction and its operation in PNC design optimization.

A case study of the China Multiproduct Pipeline (CMPL) is utilized to validate the hydraulic model and conduct sensitivity analysis. The proposed model demonstrates a deviation of 1.1% for all technical parameters except for the end-receiving station's upstream pressure. Sensitivity analysis reveals that inaccuracies in assessing variables such as elevation profile, volume escalation, and product temperature can render pipeline design outcomes unfeasible. Furthermore, neglecting crucial financial components such as fixed cost components can result in significant variations of up to 10% in CAPEX and 9% in tariffs.

As part of this research, a novel PNC design optimization framework is developed, considering the intricate relationships among decision variables and essential TEC design parameters. A Single Horizon Optimization (SHO) framework is proposed to address the constant demand volume problem statement. Extensive sensitivity analysis of various objective functions, including a novel Tariff & Carbon-emissions Multi-Objective Function (TCMOF), is conducted on the SHO outcomes of the CMPL case study. Results indicate that TCMOF delivers a well-balanced outcome, achieving reductions in overall cost, tariff, and carbon emissions by 1.98%, 1.76%, and 3.48%, respectively, in comparison to the PNC proposed in previous literature.

The study also explores various Multi-Horizon Optimization (MHO) frameworks aligned with practical industry approaches for demand-varying problem statements. The efficacy of MHO frameworks is examined by using another case study of the Central India Pipeline (CIPL). The Pumping Station MHO (PSMHO) framework is particularly noteworthy, achieving significant cost savings of INR 1 billion and reducing tariffs by INR 139 per metric ton compared to the reference PNC. Moreover, this study investigates the optimal phasing year for Pipeline Laying MHO (PLMHO), recommending the first phase design should be up to the year when demand reaches 80% of the total demand. It is also found that the PSMHO should be applied over the PLMHO with intermediate pumping stations to further enhance the TEC outcomes.

In conclusion, the proposed SHO and MHO frameworks empower designers with better decision-making capabilities for economically viable and environmentally sustainable PNC designs, providing substantial cost savings and optimizing planning for pipeline owners while ensuring minimized tariffs for users.

Acknowledgements

Gratitude fills my heart as I reflect on the journey that led to the completion of this research. I express my sincerest thanks to all individuals who, knowingly or unknowingly, played a role in facilitating this endeavour.

First and foremost, I am deeply grateful to my supervisor, Dr Sunil Kumar Khare, whose unwavering guidance, support, and insightful feedback have been indispensable throughout my doctoral pursuit. Dr Khare's expertise, encouragement, and availability, regardless of time constraints, have profoundly shaped this thesis.

I am also indebted to the esteemed members of my thesis committee whose constructive feedback, valuable suggestions, and encouragement have enhanced the quality of this research. I also wish to thank my critics, whose feedback continually motivates me to strive for excellence. Their diverse perspectives have broadened my understanding and elevated the calibre of my work. I extend sincere thanks to my critics whose insightful suggestions have continually spurred me towards higher standards of research excellence.

I am deeply thankful to UPES for furnishing the resources and facilities necessary for conducting this research. The administrative support provided by various individuals at UPES, including Dr Nilanjana Banerjee, Dr Adesh Kumar, Mr Rajeev Attri, and Mrs Shipra Tiwari has been integral to the culmination of my PhD journey.

Additionally, I am grateful for the support extended by HPCL, which enabled me to pursue my doctoral studies. I wish to express my appreciation to industry experts, notably Mr. T Jonathan Sampath Kumar (CGM, Pipeline Engineering Services, HPCL) and Mr. Mohit Krishna (DGM, Operations & Distribution, HPCL), whose technical insights were invaluable to this work.

I would like to recognize my colleagues and friends for their moral support, engaging discussions, and moments of respite during intense research periods.

My deepest appreciation goes to my family, especially my parents, I owe a debt of gratitude for their unwavering love, encouragement, and understanding throughout this journey. Their belief in me has been a constant source of encouragement and strength.

Finally, I dedicate this thesis to Mrs. Deepa Sharma, whose unwavering inspiration has served as the guiding light of my academic pursuit.

Contents

Declaration	ii
Certificate	iii
Abstract	iv
Acknowledgements	vii
List of Figures	xi
List of Tables	xii
Abbreviations	xiii
Symbols	xviii
1 INTRODUCTION	1
1.1 INTRODUCTION	1
1.1.1 Background	1
1.1.2 Pipelines Network	4
1.1.3 Components of Liquid Pipeline Network	5
1.1.4 Pipeline Design Fundamentals	8
1.1.5 Typical Pipeline Process	8
1.1.5.1 Standards and Codes	10
1.1.5.2 Fluid Mechanics Governing Equations	15
1.1.5.3 Material Science	17
1.1.5.4 Pipeline System Components	18
1.1.5.5 Pipeline Route Selection	28
1.1.5.6 Pipeline Economics	28
1.1.5.7 Carbon-Emissions	30
1.1.6 Motivation/Need for Research	30

1.1.7	Research Objectives	32
1.1.8	Research Methodology	33
2	LITERATURE REVIEW	36
3	TECHNICAL, COMMERCIAL AND ENVIRONMENT MODELLING	46
3.1	Technical Model - Pipeline Network Configuration	46
3.1.1	Pipeline Thickness	48
3.1.2	Product Velocity	50
3.1.3	Node Pressure	50
3.1.4	Dynamic Pump Efficiency	53
3.1.5	Thermal Effect	53
3.1.6	Elevation Impact	55
3.1.7	Blended Fluids	55
3.1.8	Tankage Requirement	55
3.2	Performance Parameters	57
3.2.1	CAPEX	57
3.2.2	OPEX	61
3.2.3	Overall Cost	63
3.2.4	Tariff	63
3.2.5	Carbon-Emissions	65
4	PIPELINE NETWORK DESIGN OPTIMIZATION	68
4.1	Optimization Constituents	69
4.1.1	Interdependent Decision Variables & Expanded Search-Space	69
4.1.2	Objective Function Formulation	70
4.1.3	Optimization Technique	71
4.1.3.1	Genetic algorithms	72
4.1.3.2	BPSO	73
4.1.3.3	NSGA	74
4.1.3.4	PNC Optimzer	75
4.1.4	Average Pipeline Diameter	76
4.1.5	MHO Performance-parameters Analyzer	77
4.2	Single Horizon Optimization Methodology	78
4.3	Multi-horizon Optimization Methodology	83
4.3.1	Pipeline Laying Phasing Methodology	84
4.3.2	Pumping Station Phasing Methodology	86
4.3.3	Pipeline Laying & Pumping Station Phasing Methodology	88
5	RESULTS AND DISCUSSIONS	91
5.1	Background	91
5.1.1	Hydraulic Model Validation	93
5.1.2	Input Variables Sensitivity Analysis	95
5.1.2.1	Elevation Impact	97
5.1.2.2	Product Temperature Impact	98

5.1.2.3	Volume Change Rate Impact	100
5.1.2.4	Tankage & Linefill Impact	102
5.1.2.5	SV/IPS installations, & Dynamic Carbon-emission Coefficients, Minor Losses Impact	103
5.1.2.6	OPEX & Tariff Change Rate Impact	105
5.1.2.7	Phasing, Fixed Cost Components, Depreciation Impact	106
5.1.3	SHO Outcome: China Multiproduct Pipeline	108
5.1.3.1	Mono Objective Functions	110
5.1.3.2	Mono-to-Multi Objective Functions	111
5.1.3.3	Multi Objective Functions	112
5.1.4	SHO & MHO Outcome: Central India Pipeline	114
5.1.4.1	CIPL SHO outcome:	115
5.1.4.2	PSMHO outcome:	115
5.1.4.3	PLMHO outcome:	116
5.1.4.4	PLPSMHO outcome:	117
6	CONCLUSION	119
6.1	CONCLUSION	119
6.2	FUTURE WORK	125
	BIBLIOGRAPHY	126
	A PROGRAMMING LANGUAGE	142
	B PROBLEM STATEMENT INPUTS	147
	C LIST OF PUBLICATIONS	148
	D PLAGIARISM REPORT	149
	E SIMILARITY INDEX REPORT	150

List of Figures

1.1	Research Methodology forPNC Design Optimization	35
3.1	General Pipeline Network.	47
4.1	Multi Horizon Performance Parameters Analysis	77
4.2	Single Horizon Optimization Methodology	79
4.3	Pipeline Laying Multi Horizon Optimization Methodology	85
4.4	Pumping Station Multi Horizon Optimization Methodology	87
4.5	Pipeline Laying & Pumping Station Multi Horizon Optimization Methodology	89
5.1	Pipeline Network Results in Pipeline Studio	94
5.2	Modified CMPL PNC post intermediate stations.	96
5.3	Impact of Elevation on Performance Parameters.	97
5.4	Impact of Product Temperature on Performance Parameters.	98
5.5	Impact of Volume Rate on Performance Parameters.	100
5.6	Impact of Tankage & Linefill on Performance Parameters.	102
5.7	Impact of SV/IPS installations, & Dynamic Carbon-emission Coefficients, Minor Losses on Performance Parameters.	103
5.8	OPEX & Tariff Rate impact on Performance Parameters.	105
5.9	Phasing, Fixed Cost Components, Depreciation, Cost Escalation impact on Per- formance Parameters.	106
5.10	SHO Performance for different Objective Functions	109
5.11	CIPL Reference PNC	114
5.12	Impact of Initial Phasing Year Selection on PLMHO	117

List of Tables

1.1	Friction Factor Equations	14
1.2	Pipeline Roughness Value	14
1.3	Civil Facilities	27
1.4	Pipeline Network Capacity Utilization	31
2.1	PNC Model Parameters	37
2.2	PNC Model Parameters	38
2.3	Gap Analysis Summary Table	45
3.1	Design Safety Factor on different Right-of-Use (ROU)	49
3.2	Station Facilities	59
5.1	Proposed hydraulic model outcome	93
5.2	Comparative analysis of proposed model outcome with reference paper and Pipeline Studio	94
5.3	Impact of parameters variation	108
5.4	Impact of Objective Functions on CMPL SHO	109
5.5	CIPL PNC performance for different MHO Frameworks	118
6.1	Impact of TCMOF	123

Abbreviations

ACO	Ant Colony Optimization
AIS	Artificial Immune System
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ATF	Aviation Turbine Fuel
BARON	Branch-And-Reduce Optimization Navigator
BBA	Branch & Bound Algorithm
BMRFO	Boolean Manta-Ray Foraging Optimization
BPSO	Boolean Particle Swarm Optimization
BROA	Branch-Refine-Optimize Algorithm
CA	Corrosion Allowance
CAPEX	Capital Expenditure
CCP	Chance-Constrained Programming
CE	Carbon Emissions
CFW	Civil Facilities & Works
CIDRA	CI & DRA

CIPL	Central India Pipeline
CMPL	China Multiproduct Pipeline
CMS	Corrosion Monitoring System
CPS	Cathodic Protection Station
DE	Differential Evolution
DPA	Dynamic Programming Algorithm
DRA	Drag Reducing Agent
DS	Dispatch Station
ECM	ϵ -Constraint Method
EI	Electrical & Instrumentation System
EIA	Environmental Impact Assessment
ES	Evolutionary Strategy
FPS	Fire & Protection System
GA	Genetic Algorithm
GIS	Geographical Information System
GPM	Gradient Projection Method
GRG	Generalized Reduced Gradient
HDSM	Heuristic Deep Search Method
HSD	High-Speed Diesel
IPS	Intermediate Pumping Station
IPPS	Intermediate Pigging and Pumping Station
IPRS	IPPS-cum-RS

IPS	Intermediate Pigging Station
IRR	Internal Rate of Return
ISRES	Improved Stochastic Ranking Evolutionary Strategy
LDS	Leak Detection System
LPG	Liquefied Petroleum Gas
MAOP	Maximum Allowable Operating Pressure
MHO	Multi-Horizon Optimization
MINLP	Multi Integer Non-Linear Programming
MMSCMD	Metric Standard Cubic Meters Per Day
MMTPA	Million Metric Ton Per Annum
MOPNG	Ministry of Petroleum & Natural Gas
MS	Motor Spirit
NSGA	Non-Dominated Sorting Genetic Algorithm
NS-saDEA	Elitist Non-dominated Sorting Method and Self-adapting Differential Evolution (saDE) Algorithm
OC	Overall Cost
OCMOF	Overall-cost & Carbon-emissions Multi-Objective Function
OD	Outer Diameter
OISD	Oil Industry Safety Directorate
OM	Operation and Maintenance
OP1	Optimizer 1 for number of intermediate pumping stations & their locations
OP2	Optimizer 2 for pipeline diameter
OP3	Optimizer 3 for pipeline laying phasing

OP4	Optimizer 4 for pump-station construction phasing
OPEX	Operating Expenditure
PBIT	Profit Before Income Tax
PCP	Permanent Cathodic Protection
PCV	Pressure Control Valve
PDAM	Powell Directional Acceleration Method
PLC	Programmable Logic Controller
PLMHO	Pipeline Laying MHO
PLPSMHO	Pipeline Laying & Pumping Station MHO
PLWD	Pipeline Length-Weighted Diameter
PNC	Pipeline Network Configuration
PNGRB	Petroleum and Natural Gas Regulatory Board
PS	Pumping Station
PSMHO	Pumping Station MHO
PSO	Particle Swarm Optimization
PSS	PLC & SCADA System
ROU	Right-of-Use
RS	Receipt Station
RTU	Remote Telemetry Unit
SA	Simulated Annealing
SCADA	Supervisory Control and Data Acquisition
SHO	Single Horizon Optimization

SKO	Superior Kerosene Oil
SMYS	Specified Minimum Yield Strength
SRES	Stochastic Ranking Evolutionary Strategy
STPS	Sump Tanks & Pumping System
SV	Sectionalising Valve
TCMOF	Tariff & Carbon-emissions Multi-Objective Function
TCP	Temporary Cathodic Protection
TEC	Technical-Environment-Commercial
UMDA	Univariate Marginal Distribution Algorithm

Symbols

η_0	Nominal Pump Efficiency Factor
η_p	Dynamic Pump Efficiency Factor in p^{th} year
ρ	Product Density (kg/m^3)
ρ_{15}	Product Density at 15°C (kg/m^3)
ρ_τ	Product Density at τ °C (kg/m^3)
ρ_s	Steel Density (kg/m^3)
θ_T	Slope of Tank Roof (deg)
γ_{ECE}	Dynamic Factor for Electrical Carbon Emission (%)
γ_{SCE}	Dynamic Factor for Steel Carbon Emission (%)
ρ_s	Steel Density (kg/m^3)
A_{IPS-L}	Additional Land Area required in Intermediate Pigging Station (m^2)
A_{PS-L}	Additional Land Area required in Pumping Station (m^2)
A_{RS-L}	Additional Land Area required in Receiving Station (m^2)
A_{SV-L}	Additional Land Area required in SV Station (m^2)
A_i	Area of i^{th} section (m^2)
B_{IF}	Presence/Absence of Multiproduct Pipeline
B_{IPS_i}	Intermediate Pigging Station location at i^{th} node (0,1)
B_{PS_i}	Pumping Station location at i^{th} node including DS, IPPS, and IPRS (0,1)
B_{RS_i}	Receiving Station location at i^{th} node including end-RS (0,1)
B_{SV_i}	SV Station location at i^{th} node (0,1)
b_T	Trench width (m)
C_{AD}	Administration Operating Cost Coefficient (% of C_M)
C_{AT}	Tank Associated Facilities Cost Coefficient (% of C_{TC})

C_{AX}	Auxiliary Energy Consumption Carbon Emission Coefficient (CO ₂ GT)
C_{BP}	Booster Pump Cost Coefficient (×Million INR/KW)
C_{CP}	ROU Cathodic Protection System Cost Coefficient (×Million INR/km)
C_{DS}	Addl. Facilities in DS (CI/DRA, BP) Cost Coefficient (×Million INR)
C_{ECE}	Electrical Carbon Emission Coefficient (CO ₂ GT/KWh)
C_{EN}	EIA studies and Environmental Mitigation Cost Coefficient (%)
C_{EP}	EPMC Cost Coefficient (%)
C_{E-PS}	Construction of Pumping Station along with other intermediate station Carbon Emission Coefficient (CO ₂ GT)
C_{FG}	Fugitive Carbon Emission Coefficient (CO ₂ GT/ km/MT)
C_{HVAC}	HVAC Cost Coefficient (8760×Million INR/KWh)
C_{IN}	Insurance Cost Coefficient (×Million INR PA)
C_{IPS-AE}	Auxiliary Electric Cost at IPS Coefficient (×Million INR PA)
C_{IPS-C}	Civil Supply & Erection Cost Coefficient of Intermediate Pigging Station (×Million INR)
C_{IPS-E}	Electrical Supply & Erection Cost Coefficient of Intermediate Pigging Sta- tion (×Million INR)
C_{IPS-F}	Fire Protection Facilities Cost Coefficient of Intermediate Pigging Station (×Million INR)
C_{IPS-I}	Instrumentation Supply & Erection Cost Coefficient of Intermediate Pig- ging Station (×Million INR)
C_{IPS-L}	Additional Land Lease Cost Coefficient of Intermediate Pigging Station (×Million INR/ m^2)
C_{IPS-M}	Mechanical Supply & Erection Cost Coefficient of Intermediate Pigging Station (×Million INR)
C_{LAY}	Pipeline Laying Cost Coefficient (×Million INR/km)
C_{LC}	ROU Land & Crop Compensation Cost Coefficient (×Million INR/km)
C_{LF}	Line-fill Product Cost Coefficient (×Million INR/KL)
C_{MFM}	MFM Cost Coefficient (×Million INR/(m/s))
C_{MLP}	Mainline Pump Cost Coefficient (×Million INR/KW)

C_{N-PS}	Construction of New Pumping Station Carbon Emission Coefficient (CO ₂ MT)
C_{OCP}	Cathodic Protection Cost Coefficient (×Million INR PA)
C_{ODS}	Operating Cost Coefficient for Additional Facilities in Dispatch Station (×Million INR PA)
C_{OHV}	HVAC Electric Cost Coefficient (×Million INR PA)
C_{OM-P}	Operation & Maintenance Cost of Pipeline Coefficient (% PA)
C_{OM-S}	Operation & Maintenance Cost of Stations Coefficient (% PA)
C_{OPE}	MLP Operating Electric Cost Coefficient (×Million INR PA)
C_{PC}	Pipe Steel Cost Coefficient (×Million INR/kg)
C_{PS-AE}	Auxiliary Electric Cost at PS Coefficient (×Million INR PA)
C_{PS-C}	Civil Supply & Erection Cost Coefficient of Pumping Station (×Million INR)
C_{PS-E}	Electrical Supply & Erection Cost Coefficient of Pumping Station (×Million INR)
C_{PS-F}	Fire Protection Facilities Cost Coefficient of Pumping Station (×Million INR)
C_{PS-I}	Instrumentation Supply & Erection Cost Coefficient of Pumping Station (×Million INR)
C_{PS-L}	Additional Land Lease Cost Coefficient of Pumping Station (×Million INR/ m^2)
C_{PS-M}	Mechanical Supply & Erection Cost Coefficient of Pumping Station (×Million INR)
C_{RD}	Road Transportation Carbon Emission Coefficient (CO ₂ GT)
C_{RS-AE}	Auxiliary Electric Cost at RS Coefficient (×Million INR PA)
C_{RS-C}	Civil Supply & Erection Cost Coefficient of Receiving Station (×Million INR)
C_{RS-E}	Electrical Supply & Erection Cost Coefficient of Receiving Station (×Million INR)
C_{RS-F}	Fire Protection Facilities Cost Coefficient of Receiving Station (×Million INR)

C_{RS-I}	Instrumentation Supply & Erection Cost Coefficient of Receiving Station ($\times$ Million INR)
C_{RS-L}	Additional Land Lease Cost Coefficient of Receiving Station ($\times$ Million INR)
C_{RS-M}	Mechanical Supply & Erection Cost Coefficient of Receiving Station ($\times$ Million INR)
C_{SCE}	Steel Carbon Emission Coefficient (CO ₂ GT)
C_{SE}	Soil Erosion Carbon Emission Coefficient (CO ₂ GT)
C_{SO}	Start-up Commissioning & Owner's Expenses Cost Coefficient (%)
C_{SOC}	Soil Type Coefficient
C_{SP}	Spare Cost Coefficient (%)
C_{SPT}	Surge Tank & Pump Cost Coefficient ($\times$ Million INR)
C_{SR}	Pipeline Route Survey Cost Coefficient ($\times$ Million INR/km)
C_{SV-AE}	Auxiliary Electric Cost at SV Coefficient ($\times$ Million INR PA)
C_{SV-C}	Civil Supply & Erection Cost Coefficient of SV Station ($\times$ Million INR)
C_{SV-E}	Electrical Supply & Erection Cost Coefficient of SV Station ($\times$ Million INR)
C_{SV-F}	Fire Protection Facilities Cost Coefficient of SV Station ($\times$ Million INR)
C_{SV-I}	Instrumentation Supply & Erection Cost Coefficient of SV Station ($\times$ Million INR)
C_{SV-L}	Additional Land Lease Cost Coefficient of SV Station ($\times$ Million INR/ m^2)
C_{SV-M}	Mechanical Supply & Erection Cost Coefficient of SV Station ($\times$ Million INR)
C_{SX}	RoU Excavation Carbon Emission Coefficient (CO ₂ GT)
C_{TC}	Tank Steel Cost Coefficient ($\times$ Million INR/kg)
C_{TEL}	Pipeline Telecom & SCADA System Cost Coefficient ($\times$ Million INR/km)
C_{TNC}	Pipeline Transportation & Coating Cost Coefficient (% of C_{PC})
C_C	Contingency Cost Coefficient (%)
C_L	Land Maintenance Cost Coefficient ($\times$ Million INR/Acre PA)
C_M	Manpower Operating Cost Coefficient ($\times$ Million INR/Person PA)
$CAPEX$	Total Capital Cost of Pipeline Project ($\times$ Million INR)
$CAPEX_p$	Capital Cost of Pipeline Project in p^{th} year ($\times$ Million INR)

CE	Total Carbon Emission (CO2 GT)
cpi	Consumer Price Index (%)
D_A	Diameter of Annular Plate of Tank (m)
D_B	Diameter of Bottom Plate of Tank (m)
D_e	Equivalent Diameter of parallel lines in section
D_i	Internal Diameter in of i^{th} section
d_M	Depreciation Rate of Mechanical Assets (%)
D_S	Total Daily Sales Volume
D_T	Diameter of Tank Shell (m)
DE_{C_p}	Depreciation Value of Civil Assets in p^{th} year ($\times$ Million INR)
DE_{M_p}	Depreciation Value of Mechanical Assets in p^{th} year ($\times$ Million INR)
DE_{P_p}	Depreciation Value of Pipe Assets in p^{th} year ($\times$ Million INR)
DE_{PM_p}	Depreciation Value of Plant & Machinery Assets in p^{th} year ($\times$ Million INR)
DE_p	Total Depreciation Value of Assets in p^{th} year ($\times$ Million INR)
df	Discount Factor (%)
E	Total Carbon Emission (CO2 GT)
Ex_{HP}	Excavator Power (HP)
Ex_B	Excavator Bucket Size (m^3)
Ex_C	Excavator Cycle Time (s)
Ex_E	Excavator Work Efficiency Rate (%)
f_{e_i}	Equivalent friction factor of parallel lines in i^{th} section
f_i	Friction factor at i^{th} node
F_k	Design Safety Factor of k^{th} section
h_{T_i}	Trench height in section (m)
H_T	Height of Tank Shell (m)
I_i	RoU Cost Impact Factor at i^{th} node
irr	Internal Rate of Return (%)
IT	Income Tax rate (%)
IT_p	Income Tax in p^{th} year (Million INR)
J	Seam Joint Factor
L	PNC Total Length (km)

L_{MP}	Distance of Steel Manufacturing Plant to Pipeline Mid-point (Km)
L_i	Length of i^{th} section (km)
M_{IPS}	Intermediate Pigging Station Manpower PA
M_{PS}	Pumping Station Manpower PA
M_{RS}	Receiving Station Manpower PA
M_{SV}	SV Station Manpower PA
N	Analysis Period (years)
O_{IPS}	Intermediate Pigging Station Cost ($\times$ Million INR)
O_{PS}	Pumping Station Cost ($\times$ Million INR)
O_{RS}	Receiving Station Cost ($\times$ Million INR)
O_S	Total Cost of all Stations ($\times$ Million INR)
O_{SV}	Sectionalising Valve Station Cost ($\times$ Million INR)
O_E	Total Operating Cost of Energy Consumption ($\times$ Million INR PA)
O_L	Total Operating Cost of Land ($\times$ Million INR PA)
O_M	Total Operating Cost of Manpower & Admin. Coefficient ($\times$ Million INR PA)
O_p	Pipeline Cost ($\times$ Million INR)
OC	Overall Cost ($\times$ Million INR)
OD_i	Outer Diameter of i^{th} section (m)
op_E	Operating Cost Escalation (%)
$OPEX$	Total Operating Cost ($\times$ Million INR)
$OPEX_p$	Operating Cost in p^{th} period ($\times$ Million INR PA)
P_{A_j}	Branch-line Pressure required at j^{th} section (Kg/cm^2)
P_{B_i}	Minimum Back-pressure required at i^{th} node (Kg/cm^2)
P_{D_i}	Discharge Pressure required at i^{th} node (Kg/cm^2)
P_{E_i}	Elevation Pressure at i^{th} node (Kg/cm^2)
P_{F_i}	Friction Loss at i^{th} node (Kg/cm^2)
$P_{KW_{ip}}$	Pump Power of i^{th} node in p^{th} year (KW)
P_{M_i}	Minor Pressure Loss at i^{th} section (Kg/cm^2)
P_I	Internal Pressure (Kg/cm^2)
$PBIT_p$	Profit before Income Tax in p^{th} year (Million INR)

PH_p	CAPEX Phasing Ratio in p^{th} year (%)
PH_t	CAPEX Phasing Ratio in
Q_{k_p}	Flow Rate of k^{th} section in p^{th} period (KL/hr)
Q_0	Pump Rated Flow Rate (KL/hr)
Re_{x_i}	Intermix Reynold's Number in i^{th} section
S_{P_t}	Steel Line Pipe Quantity (Kg) in t^{th} year (kg)
S_{T_i}	Steel required for Tank in t^{th} year (kg)
S_{TA}	Steel required for Tank Associated Facilities (kg)
S_k	Allowable stress of k^{th} section
SM_{DS}	Contingency Days for Sales Volume (days)
SM_{IF}	Safety Margin on Intermix Theoretical Calculation
T	Pipeline Tariff (INR/MT)
t_{AT}	Thickness of Annular Plate of Tank (m)
t_{BT}	Thickness of Bottom Plate of Tank (m)
t_{RT}	Thickness of Tank Roof (m)
t_i	Pipe Thickness of i^{th} section (m)
T_O	Total Pumps Operational Hours during Analysis Period (hours)
t_T	Thickness of Tank Shell (m)
t_v	Volume Escalation
TA	Total Tankage at end-node RS (KL)
ta_E	Tariff Escalation (%)
TC_M	Total Cost of Mechanical Assets ($\times$ Million INR)
V	Product Demand Volume (MT)
v_{E_k}	Economical Velocity in k^{th} section (m/s)
V_i	Demand Volume in i^{th} section
v_i	Velocity in i^{th} section (m/s)
v_U	Upper-limit of Velocity (m/s)
w_{AT}	Width of Annular Plate of Tank (m)
w_C	Coating Width (m)

Dedicated to My Mother.

Chapter 1

INTRODUCTION

1.1 INTRODUCTION

1.1.1 Background

Crude oil, a refined petroleum product, is a naturally occurring liquid composed primarily of hydrocarbons and trace amounts of metals. This raw material can be refined to produce various products, including petrol, kerosene, diesel, and other petroleum & petrochemical products. Scientists have found that crude oil is found beneath the earth's surface in geological formations, formed from the remains of a large number of dead organisms, right from the single-celled algae to the complex animal forms, which were buried under sedimentary rock layers. These organisms absorbed energy from the sun, storing it as carbon. They descended into the ocean floor upon their death and became buried under sediment deposits. Over millions of years, they are converted into oil after exposure to intense heat and pressure-triggered chemical reactions. Due to this long formation process, oil cannot be produced artificially and is therefore considered a non-renewable energy source. After formation, oil migrates from the source rock through seeps or pores in surrounding rocks and becomes trapped beneath impermeable layers like clay, forming oil reservoirs. The majority of the oil deposits formed during the Mesozoic era, with subsequent formations occurring during the Cenozoic and Paleozoic eras [112]. Refineries are complex processing plants that vary in type based on the end products they produce, ranging from petroleum fuels to salts. Crude oil is classified by quality, determined by its sulfur content (sour to sweet) and density (heavy to light). After extraction, it is transported to refineries where it undergoes chemical and mechanical processes to produce petroleum products like diesel, kerosene, and other derivatives. Sweet, light crude is more valuable and requires less processing

than sour, heavier crude, making it the preferred choice for high-value products such as petrol, diesel, and aviation fuel. The petroleum industry encompasses the global processes of these products' exploration, extraction, refining, transportation, and marketing.

The use of petroleum dates back over 4,000 years, with ancient civilizations such as the Egyptians using it to prepare mixtures for embalming their dead and Babylonians using it in medicine and lighting [59]. The invention of the combustion engine and the rise of commercial aviation have significantly increased the importance of petroleum in modern times. For centuries, coal was a cornerstone of technological progress in transportation, agriculture, and manufacturing, as well as a major energy source for electricity generation, cement production, and steel manufacturing. However, in the twentieth century, oil surpassed coal as the dominant energy source, becoming essential to sustaining modern life [59]. Petroleum is vital to numerous industries and is fundamental to maintaining industrial civilization in its current form, making it a critical concern for many nations. Additionally, petroleum is the raw material for a wide array of chemical products, including solvents, pharmaceuticals, fertilizers, plastics, and pesticides.

Oil dominates as a major energy source, as it constitutes 30.9% of the primary energy supply of the world, and forecasts suggest a steady growth in global demand, anticipated to increase by 0.6% annually until 2026 [85, 84]. India is the third-largest consumer of crude oil globally, following the USA and China [125]. By 2025, China and India are projected to account for more than half of the global oil demand [83]. Moreover, by 2030, India is projected to contribute more than one-third of the global oil demand growth, making it the single largest source of demand growth from 2023 to 2030, just ahead of China [118].

Despite this rising demand, India's domestic crude production has remained stagnant for the past three decades and has even decreased over the past ten years, accounting for only 0.75% of global crude production. India has emerged as the world's 2nd largest net importer of crude oil, with imports increasing by 36% over the past decade to meet the growing demand from refineries [118]. The widening gap between crude oil supply and demand has driven up petroleum product prices, affecting multiple economic sectors. To mitigate the cost impact on end consumers, it is crucial to choose the most efficient and economical methods of transporting petroleum products.

Transportation via air, sea, rail, road and pipeline is an indispensable and fundamental necessity of society alike water, food, and air [78]. Optimizing transportation costs is crucial for reducing the overall cost of petroleum products [45]. There are several modes of transporting petroleum products from refineries to distribution stations, including tank trucks, railway tankers, ships, pipelines, and barges [48]. For transporting products from distribution stations to end customers, the common methods include tank trucks, pipelines, and railway tankers. The selection of

the transportation method relies on various factors, including the type of product, distance, expenses, and the presence of alternative options. Transporting petroleum products across a vast country like India presents significant challenges. Pipelines play a vital role in this context, as they are the safest, most economical, fastest, and most efficient method for transporting large volumes of petroleum products [62]. Hence, pipelines are the arteries of the nation's economy.

Pipeline transportation costs are significantly lower than other methods: it is 20 times cheaper than road transport, 10 times cheaper than rail, and twice as economical as waterways [162]. Pipelines can traverse large distances, crossing water bodies such as rivers, creeks, and ponds, with the flexibility to be laid both above and below ground. Therefore, investing in pipeline infrastructure is essential to ensure a secure, cost-effective, rapid, and energy-efficient method for transporting substantial quantities of petroleum products across extensive distances [48, 103, 45, 160, 169, 182, 57]. Implementing a well-designed pipeline network can significantly reduce supply chain costs, making it the preferred option for large-scale oil transportation [160]. However, it's important to acknowledge that constructing a pipeline network requires significant capital investment and has long-term implications for the entire supply chain.

Pipeline projects demand substantial capital investment, so even minor improvements in pipeline design can lead to significant savings in both capital and operating costs. However, PNC depends on various factors, including economic conditions, topological complexities, and technical constraints. Traditionally, these factors are assessed through conventional trial-and-error methods, relying heavily on the design engineer's experience and judgment. With numerous possible pipeline design solutions, this approach has a high risk of sub-optimal results [80]. Such inefficiencies increase computation time and can lead to unnecessary investments, negatively impacting society economically, socially, and environmentally. Traditionally, designing of the PNC considering these factors is assessed through conventional trial-and-error methods based on the experience and judgment of design engineers. However, numerous potential pipeline design solutions exist for any given pipeline design problem statement, and the trial-and-error approach may yield suboptimal results. Hence, this not only increases computation time but also risks leading to unnecessary investments, which can negatively impact socioeconomic and environmental impact. Notably, it is also evident that the pipeline infrastructure is often underutilized in India, operating at only up to 70% of its installed capacity [147]. Therefore, there is an urgent need to develop holistic pipeline optimization system-based solutions that consider technical, financial, and all other relevant variables. This comprehensive framework would enable the creation of an economic and efficient petroleum supply chain network, benefiting the owner, users, and end customers alike.

As pipeline networks grow in complexity, heuristic methods, reliant on human decision-making, become less effective, paving the way for system-based techniques to offer higher cost reductions [60]. Various optimization algorithms available in the literature provide more detailed pipeline cost reductions compared to traditional heuristic approaches. These sophisticated techniques drastically reduce the computation time of pipeline design from hours or days to just minutes and lower the overall investment needed [80, 60]. It's important to note that this research doesn't support the complete replacement of human judgment; rather, it aims to supplant the intricate and time-intensive trial-and-error processes typically employed by engineers. By proposing a system-based optimal design framework for pipeline networks, this research seeks to provide substantial savings for pipeline owners in terms of cost and planning. Additionally, it benefits end customers by minimizing pipeline tariffs and reducing carbon emissions.

1.1.2 Pipelines Network

Pipeline transport serves as a vital method for conveying goods or materials through a network of pipes. The most recent data indicates a staggering total of over 39 million kilometres of pipelines spread across 130 countries worldwide [49]. Notably, the United States, Canada and Russia have the most expansive pipeline networks, a testament to their significant energy production and consumption capacities. Additionally, countries such as China, and India maintain substantial pipeline infrastructures, pivotal for fulfilling their energy requirements and supporting industrial endeavours. Remarkably, the United States holds 63% of the global pipeline network, followed by Canada with 22%, while Russia and China contribute 7% and 4% respectively, collectively accounting for 96% of all pipelines [49]. These statistics underscore the pivotal role certain nations play in shaping the global energy transportation landscape, emphasizing the indispensable nature of pipeline networks in facilitating energy movements within major energy-producing and consuming nations.

Countries such as the USA, Canada, and Russia boast established pipeline networks, while emerging economies like India and China are rapidly expanding their own systems [127, 177]. India, in particular, is aggressively expanding its existing oil and gas pipeline infrastructure span of approximately 50,081 km projected to reach 63,267 km in the coming years. This expansion is expected to contribute around INR 1 trillion to the economy, which is approximately 20% of the total MoPNG budget [123]. In the petroleum industry, pipelines are commonly classified into three main types:

1. **Gathering Pipelines:** These pipelines connect oil or natural gas wells to centralized tank farms for storage or treatment. They have relatively small diameters, operate at low pressures (below 7 kg/cm^2) and typically range from 2 to 4 inches.
2. **Crude Pipelines:** These pipelines link storage facilities at oil wells or import terminals to refineries. In India, the crude pipeline network covers 10,419 kilometres and has a capacity of 159 Million Metric Ton Per Annum (MMTPA) [123].
3. **Product Pipelines:** These pipelines transport refined petroleum products from refineries to storage tanks or directly to consumers. They handle a variety of products including Aviation Turbine Fuel (ATF), High-Speed Diesel (HSD), Motor Spirit (MS), Liquefied Petroleum Gas (LPG), and Superior Kerosene Oil (SKO). India's network for refined petroleum product pipelines covers 19,033 km with a capacity of 115.70 MMTPA, alongside a natural gas pipeline network of 20,629 km with a capacity of 332.9 Metric Standard Cubic Meters Per Day (MMSCMD) [123]. Typically, the diameters of crude & product distribution pipelines range from 12-24 inches, though sometimes they can extend up to 42 inches.

1.1.3 Components of Liquid Pipeline Network

Liquid petroleum products, including diesel (42%), petrol (14%), and LPG (5%), collectively contribute to 61% of total consumption in India [125]. Pipeline networks consist of various components working together to transport products from one location to another. According to [129, 140], a pipeline system comprises pipes that transport liquid hydrocarbons, along with associated facilities such as pumps, storage units, metering systems, line balancing tanks, inter-face tankages, safety measures, valves, equipment, tool launchers/receivers, corrosion protection systems, manifolds, and other accessory equipment essential for operating the network. Here are some definitions of the main elements of a pipeline system:

1. **Trunkline or mainline pipelines**, also known as cross-country pipelines, encompass all liquid hydrocarbon pipelines present outside the pipeline station facility. In contrast, pipelines dedicatedly serving terminal or customer destinations are termed Branch Pipelines.
2. The portion of land where the pipeline is laid and operated, acquired either through the PMP Act'1962 or by agreement with the agency/landowner, is known as Right-of-Way or ROU.

3. **Originating Pumping Station/Dispatch Station (DS):** The primary pipeline station that serves as the point where the product is injected into the pipeline. An initial pump station acts as the starting point along the cross-country pipeline, featuring pumps that elevate the pressure of the liquid hydrocarbons for efficient transport to the next station along the route [129]. It incorporates pumps and associated systems to overcome pressure losses in subsequent sections.
4. **IPPS:** IPPS are constructed to increase the pressure of pipeline products required to reach the next station. These pumping stations are strategically positioned along the mainline to counter pressure losses in intermediate sections. Their locations are determined by factors such as terrain, product specifications, and process variables. An intermediate pump station is equipped with pumps and situated between the originating pump station and either an intermediate pigging station or a terminal/receipt station. Its purpose is to enhance the pressure of the liquid, ensuring its transit to the subsequent station(s) along the pipeline route [129].
5. **Intermediate Receipt Station (RS):** Installations equipped to deliver products to customer-s/storage tanks through heart cut or full cut tapping from the mainline are referred to as Tap-off Stations or Intermediate Delivery Stations. These stations receive a portion of the product destined for end-receiving stations. Terminal facilities are utilized here to further distribute the product to end customers through retail outlets or bulk consumer tanks. An intermediate delivery station, also referred to as a tap station along the pipeline installation, is a facility designed to distribute products to industries or storage tanks by tapping into the mainline [129]. This distribution can be achieved through either a heart cut or a complete tap. Stations constructed alongside intermediate receipt stations are known as IPPS-cum-RS (IPRS).
6. **End-RS:** The final station in the pipeline network, equipped similarly to intermediate receiving stations, along with tankages for managing intermix generated during product transportation.
7. **IPS:** PIG, short for “Pipeline Inspection Gauge,” are also known as scrapers. They are utilized for cleaning pipelines (mechanical pigging) and/or inspecting pipeline integrity (intelligent pigging) [137]. An intermediate pigging station is a facility equipped to receive and launch pigs used in pipeline cleaning/maintenance and inspection operations. As per [129], all cross-country pipelines, feeder lines, spur lines, and branch lines with a diameter of ≥ 4 inches and a length of ≥ 10 km should have pigging facilities. Intermediate stations equipped with pig receiving and launching facilities are referred to as Intermediate Pigging Stations (IPS). These stations serve various purposes, including facilitating operations

such as changing pipe diameter, adjusting wall thickness, and applying internal coating. The distance between successive stations is determined by factors such as the type of product being transported, pipeline diameter, pigging operation nature and the capabilities of the pigging equipment. To ensure accessibility, pigging stations should be connected to all-weather access roads from the nearest road. When positioning pig traps, safety considerations for access routes and adjacent facilities must be taken into account. Pigging facilities must be designed to include handling of pigs, access to pig traps, direction control for pigging (including bi-directional), isolation needs for pig launching & receiving, drainage for muck or condensate during operations, spacing between bends or fittings, minimum bend radius requirements, variations in pipe diameter & wall thickness, internal coatings, and pig signalling mechanisms [129].

8. SV Station: Motorized Operated Valves/ Hand Operated Valves, used for isolating particular pipeline sections necessary for operations & maintenance and limiting the pipeline accidents, are called Sectionalizing Valves (SV) or Main Line Valves. SVs are installed in all DS, IPPS and RS, with the distance between two consecutive SVs being equal to or less than 50 km [129]. To comply with regulatory requirements for SVs along the pipeline ROU, it is necessary to install SVs not only at mainstations but also at intermediate locations known as Sectionalizing Valve Stations. SV Stations are also present upstream and downstream of perennial rivers, fulfilling statutory requirements of pipeline projects and factored into pipeline network design. SV station location also considers factors like ease of operation, location topography, and maintenance requirements. No overhead power lines should pass directly over the SV Station. Check Valves are also installed to prevent reverse product flow within the station, considering terrain features like steep slopes and hills. Hence, SV placement needs to be considered before such terrain features. These critical stations are crucial for isolating sections of the mainline in case of leaks, ruptures, hazards, or maintenance needs by using valves (motorised or hand-operated). Thus, they serve as the primary line of defence for cross-country pipelines. SV stations should be strategically located in easily accessible areas, ideally close to main roads. They should also have a dedicated access route connecting them to the nearest all-weather paved road. These installations must be secured by enclosing the facilities with a suitable boundary wall or fencing, along with a gate for entry. The pipeline SV can be operated manually, electrically, pneumatically, or hydraulically, with provisions for remote operation as per the operation and control philosophy determined by the pipeline owner. When SV stations are constructed along with pump or repeater stations, it is essential to adhere to safe distance requirements and statutory clearance regulations [129]. Preferably, SV on the main pipeline should be full-bore ball valves that meet the minimum standards outlined

in ISO-14313 (Specification for Pipeline Valves) [94] or API-6D [9]. Additionally, suitable corrosion protection coating should be applied to the valve surface to enhance its durability and longevity.

1.1.4 Pipeline Design Fundamentals

1.1.5 Typical Pipeline Process

1. General Control Philosophy: The overall control philosophy outlines the critical role of the instrumentation control system in assuring the secure and effective operation of the pipeline project. A Programmable Logic Controller (PLC)-based control system is required at the pumping station, receiving station, and intermediate station to manage process interlocks, shutdown logic, operation of Motor motor-operated valves, control and monitoring of field instrument signals, and station monitoring & control. Additionally, a dedicated control panel are installed to manage field instruments and process interlocks effectively. Furthermore, a metering panel equipped with a flow computer is necessary for the monitoring, analysis, and accounting of the product.
2. Batching: Batching involves transporting multiple products simultaneously through a pipeline with minimal mixing, which is critical for efficiently moving products like diesel, petrol, and kerosene from refineries to storage terminals. While some blending of batches is inevitable at the boundaries of adjacent batches. Operating the pipeline flow in turbulent mode with sufficiently high velocities is propounded to reduce product contamination. Laminar flow would result in more intermingling of product batches, potentially degrading product quality. Additionally, batched pipelines must operate under packed conditions, avoiding slack lines or open channel flow, especially in pipelines with significant elevation changes. Determining the optimal batch size for different products in the pipeline system is essential for economical operation and minimizing pumping costs. This involves analysing flow rates and pumping costs over a defined period, such as a week or a month. The optimal batch size is the combination that results in the lowest total pumping cost while needs of meeting pipeline owner, user, and market demands.
3. Dispatch Station/Pumping Station: The product will be transferred from the tankage by gravity to the booster pumps, where it will undergo pressurization to 5-8 kg/cm^2 before being directed to the suction of the main line pumps via filtration and metering. Before product pumping, it will undergo filtration using a basket filter and then metered using a mass flow meter. A dedicated flow computer, equipped with pressure and temperature

compensation, should be provided for accurate flow monitoring. Consequently, the main line pump will further increase the pressure from 5 kg/cm^2 to a higher pressure depending upon pump & pipeline design pressure. Variable frequency drives can be installed to operate the pump dynamics instead of DOL operations. A redundant 2oo3 pressure instrumented trip system should be provided to initiate pump shutdown in the event of high pressure. Furthermore, corrosion monitoring will be facilitated through the provision of corrosion coupons and probes.

A corrosion inhibitor package should be installed for injecting chemicals into the piping system to prevent internal corrosion of pipelines. A cathodic protection system shall be implemented to safeguard against external corrosion. A Drag Reducing Agent (DRA) skid is utilised to inject DRA, minimising turbulence within the pipeline. Both the corrosion inhibitor and DRA will be injected at the inlet header of the mainline pumps.

A fire water network should be established at both the pump station and process facilities. Adequate fire and gas detectors should be installed strategically, with signals transmitted to the control room. A dedicated closed drain tank and sump pump should be installed at the dispatch station, ensuring efficient drainage.

Pig traps should be provided, and the pipeline should be designed for intelligent pigging operations. Thermal relief valves should be installed at critical locations to manage pressure build-up caused by solar radiation during blocked discharge scenarios.

A single SCADA system shall be employed to manage the entire pipeline network. Power should be supplied from the existing high-tension power source, with a suitable diesel generator (DG) set provided as an emergency backup.

4. SV and IPS will be installed along the pipeline. Fire and gas detectors should be strategically placed at SV and IPS, with signals transmitted to the DS/RS control room via RTU/SCADA through OFC (dedicated and leased backup line). Each IPS should be equipped with a dedicated closed drain tank, sump pump, and slop pump, as well as a pig launcher and receiver. Power should be supplied from the grid, with an appropriate DG set or solar power system provided for emergency backup.
5. Tap-off Station/Receiving Station: The product will be received and filtered through a basket filter before being sent to the Tap-off Station tankage to meet local demand. A dedicated closed drain tank (sump tank) and sump pump should be installed at the receipt station. This station should be equipped with a pig trap and designed for intelligent pigging. Fire and gas detectors should be strategically located, transmitting signals to the control room. A fire water network should be installed for process facilities. Thermal relief valves should be strategically placed to manage pressure build-up due to solar radiation

during block discharge scenarios. Power should be supplied from the existing source or grid. Additional tankages should be provided to meet demand requirements.

1.1.5.1 Standards and Codes

Highways are major roads that span long distances and their route affects the environment and people around it, likewise pipelines impact sociologically and environmentally along its route. Hence, its title includes the word “transportation” in pipeline standards and codes. These regulatory frameworks provide guidelines for the pipeline design, construction, & operations to mitigate any inadvertent impact on society & ensure personnel safety. Several international codes and standards addressing these concerns include:

1. American Society of Mechanical Engineers (ASME) B 31.4 – “Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids”: This code offers thorough guidelines for designing, constructing, and operating pipeline transportation systems, including references to required material specifications, dimensional requirements, design of assemblies and components, evaluation of stresses, guidance on material and component selection, piping examination requirements, inspection and testing procedures, and steps for operation and maintenance to ensure public safety. Additionally, it addresses provisions for internal/external corrosion protection [23]. Similarly, ASME B 16.34 standard applies to the construction of valves, covering dimensions, tolerances, pressure-temperature ratings, testing procedures, and other specifications for valves made of steel and other alloys [180, 18]. These codes offer basic design guidelines and specific requirements to assist in the selection and application of piping elements, but it is not a comprehensive design handbook. The ASME [23] advises designers that the code is not a substitute for competent engineering judgment. While the code provides fundamental design principles and formulas, it must be complemented with sound engineering judgment to ensure effective application.
2. American Petroleum Institute (API) 5L – “Specifications for Line Pipe”: This standard covers the specifications for different types of pipes, such as seamless or welded steel line pipes, as well as those with plain, threaded, or belled ends, and through-the-flowline pipes. These specifications ensure the suitability of pipes for transporting water, oil, and gas. API 5L pipes are available in different sizes (outside diameter), ranging from 6.625 inches to 80 inches. The specification also outlines chemical and mechanical specifications such as maximum yield strength, maximum tensile strength, test pressure, carbon composition, and testing procedures for different standard grades [11].

In addition to the above-mentioned international standards, each country establishes its codes and standards for pipeline design and engineering to meet specific requirements. Examples include the National Energy Administration in China [3], the Federal Agency for Water Resources in Brazil [65], Gazprom in Russia [70], the Japan Gas Association [30], the Canadian Standards Association [29], the European Committee for Standardization [63], the British Standards Institution [88], Standards Australia [32], the International Organization for Standardization [64], and the Deutsches Institut für Normung [66], among many others. In India, the Ministry of Petroleum & Natural Gas (MOPNG) oversees various aspects of the hydrocarbon industry, including exploration, production, refining, import/export, distribution/marketing, and conservation [123]. Under the MOPNG, the Oil Industry Safety Directorate (OISD) serves as a technical arm responsible for formulating standards aimed at enhancing safety and reducing inherent risks in the petroleum industry. OISD conducts safety audits to ensure compliance with these standards on a self-regulatory basis by oil and gas companies. Its standards cover all activities in the hydrocarbon industry, from exploration to refining, processing, storage, and distribution. Moreover, OISD continuously updates its standards to align with the latest technologies, designs, and operating practices practised in developed countries, ensuring that codes and standards are suitable for prevailing conditions in India.

1. OISD Standard 141 – “Design and Construction Requirements for Cross-Country Hydrocarbon Pipelines”: This standard stands as a primary reference for constructing pipeline networks [129]. While largely based on ASME B 31.4, it takes precedence over ASME B 31.4 in discrepancy cases. Key points include:
 - (a) “Pipeline Owner” term refers to an entity, whether an individual, corporation, public agency/organization, partnership, or any other legal entity, that holds ownership of the cross-country pipeline system.
 - (b) “Pipeline Operating Company” term refers to any individual, corporation, public agency/organization, partnership, or other entity responsible for operating a cross-country pipeline. The supplier entity owns and operates the pipeline system for delivering to multiple industries or oil marketing companies.
 - (c) Internal Design Pressure refers to the maximum steady-state operating pressure, factoring in frictional loss pressure, backpressure, and static head pressure, established through the applicable design procedure specific to the materials and locations involved.
 - (d) Maximum Operating Pressure is the highest operating pressure during a normal operating cycle, while the Maximum Allowable Operating Pressure (Maximum Allowable

- Operating Pressure (MAOP)) signifies the highest allowable operating pressure. The Design Pressure should be equal to or exceed the MAOP.
- (e) Specified Minimum Yield Strength (SMYS) term denotes the minimum yield strength of a material specified by a standard or specification, which determines the strength of the material procured from the manufacturer. The Safety Design Factor term refers to the percentage factor applied to the material SMYS to calculate the wall thickness of the pipe, based on the pipeline's location and operational requirements.
 - (f) Reconnaissance Surveys should explore all feasible routes, with alignment finalized thereafter. Route selection prioritizes public safety, avoiding populated areas, city limits, reserve forests, national parks, marshy/waterlogged areas, and mining zones. Additional considerations include ease of construction, maintenance accessibility, population density, and minimal electrical interference. No permanent structures are permitted within the ROU.
 - (g) Right-of-Way (RoW)/ ROU, the term describes the designated area or segment of land where the pipeline owner has acquired legal rights, either through the PMP Act 1962 or through an agreement with the landowner or relevant agency, to lay and operate a cross-country hydrocarbon pipeline [129, 71]. Typically, these rights do not involve the transfer of land ownership.
 - (h) Pipeline crossings of facilities (e.g., roads, highways, railways, rivers) ideally occur at close to 90-degree angles, with Turning Points located at least 50m from crossings.
 - (i) Pipes with a diameter equal to or greater than 4" NB are categorized as cross-country pipelines, necessitating a wall thickness equal to or greater than 5.5 mm. The nominal thickness is calculated per ASME B 31.4, ensuring a diameter-to-thickness (D/t) ratio of less than 100. No additional corrosion wall thickness allowance is necessary if the pipe is protected with anti-corrosion measures such as a cathodic protection system. Pipe thickness varies inversely with the Design Safety Factor based on Pipeline ROU location.
 - (j) Underground pipes and their components must be protected against corrosion by using suitable external anti-corrosion coatings or paints along with the implementation of a cathodic protection system. Similarly, above-ground piping and its components should also be safeguarded from corrosion through appropriate anti-corrosion coatings. When these corrosion protection measures effectively protect the pipe and its components, an additional pipe wall thickness allowance for corrosion protection may not be necessary.

2. The Petroleum and Natural Gas Regulatory Board (PNGRB) was established under the PNGRB Act 2006 to safeguard the interests of consumers and entities, foster competitive markets, ensure a consistent and sufficient supply of petroleum products, and oversee activities pertaining to the petroleum industry, including refining, processing, storage, transportation, distribution, marketing, and sales. Key aspects of the Technical Standards and Specifications outlined by the PNGRB for petroleum product pipelines include:
 - (a) The test pressure should be established at 1.25 times the design pressure.
 - (b) The maximum steady-state operating pressure and static head pressure during steady-state conditions should not surpass the internal design pressure. Additionally, any pressure surges or fluctuations should not exceed 1.1 times the internal design pressure.
 - (c) A "section" is a pipeline segment between an entry point and either an exit point or the next entry point in the flow direction. Calculations for successive sections start from the second entry point and proceed in sequence.
 - (d) A "spur line" refers to a pipeline that branches off from a trunk, transmission, sub-transmission pipeline, another spur line, or a terminal station connected to an existing transmission or trunk pipeline. Typically, its diameter and capacity do not exceed those of the trunk or transmission pipeline, and it does not include pumping facilities. A Spur/Branch Pipeline, which starts from the main cross-country pipeline (alias trunkline pipeline), serves a dedicated terminal and/or customer location(s).
 - (e) The pipeline's capacity is defined by the maximum flow achievable within the pipeline system under prevailing conditions, including the MOAP at the dispatch station and intermediate points in the direction of flow. This evaluation encompasses all technical and operational parameters defined for each section of the pipeline under steady-state conditions, including variables like flow rate, pressure, and temperature. The entity responsible shall provide the capacity of the pipeline and each section through steady-state simulations, accompanied by the hydraulic gradient. For liquid pipelines, the declared capacity is measured in MMTA (million tonnes per annum) of petroleum or petroleum products that the pipeline can transport under operating steady-state conditions.
 - (f) "Section capacity" refers to the maximum flow capacity of a pipeline segment, encompassing supply sources, delivery sources, or both. It signifies the highest flow rate that the section can accommodate without disrupting the supply or delivery conditions for the pipeline users.

- (g) Pipeline capacity shall be calculated on the flow equation approved by the PNGRB and/or selected software package, which supports the approved flow equation. The following flow equation is used to calculate the friction factor:

TABLE 1.1: Friction Factor Equations

Petroleum and Petroleum Products	Colebrook White [50]
Natural Gas	Panhandle Modified
for Pipe size $\geq 24''$	Panhandle B
for Pipe size $\leq 24''$	Panhandle A

- (h) Steady-State Simulation components which shall be considered are:

- i. Roughness – It is unevenness inside a pipe and value is dependent on the pipe material as mentioned below.:

TABLE 1.2: Pipeline Roughness Value

Type of Material	Roughness (micron)
Steel – Old Pipe (more than 10 years)	
Without internal coating	40-45
With internal coating	15-20
Steel – New Pipe	
Without internal coating	35-40
With internal coating	10-15

- ii. Velocity – The maximum permissible velocity for petroleum products in the pipeline is 2 m/s, while for natural gas, it is 20 m/s.
- iii. Characteristics of High-Speed Diesel (HSD) shall be considered for a multi-product pipeline.
- iv. The number of operation days should be 345 days (20 days/year is excluded for maintenance).
- v. Discharge Pressure represents the highest pressure available at the pipeline system's entry point. Conversely, Suction Pressure indicates the minimum pressure required by the customer at the delivery or exit point, as stipulated in the access agreement between the owner and the customer.

1.1.5.2 Fluid Mechanics Governing Equations

Fluid mechanics principles form the foundation for calculating pipeline flow, friction loss, pressure drop, and pumping requirements. This involves applying material balance and momentum conservation equations to the network's basic elements, forming the modelling core. Through these equations and inequalities, the pipeline network's dynamic conditions, such as pressure and flow rate, are determined.

1. Continuity Equation (Conservation of mass): The continuity equation, a fundamental principle in pipe flow, asserts that the total fluid volume passing through any section of a pipe remains constant. In essence, it signifies that liquid neither appears nor disappears as it travels through a pipeline. This adherence to the Law of Conservation of Mass ensures that the mass of the product remains consistent throughout various sections of the pipeline. Generally, the conservation of mass can be mathematically represented by the following equation, which applies to unidirectional flow:

$$\frac{\partial(\rho \times v)}{\partial x} + \frac{\partial \rho}{\partial t} = 0 \quad (1.1)$$

The relationship between mass flow rate, often referred to as pipe throughput, density, and product velocity is depicted in the equation above. The continuity equation for fluid flow between two points (A & B) is given by:

$$\dot{m} = \rho_1 \times A_1 \times v_1 = \rho_2 \times A_2 \times v_2 \quad (1.2)$$

The bulk modulus of a liquid quantifies its compressibility, representing the pressure needed to induce a unit change in volume. Typically ranging between 250,000 to 300,000 psi for most liquids, this relatively high value highlights the liquids' considerable resistance to compression [119]. Because liquids are generally considered incompressible, their density remains consistent and shows minimal variation with changes in pressure. The continuity equation for liquids can be expressed as follows:

$$Q = A_1 \times v_1 = A_2 \times v_2 \quad (1.3)$$

2. Energy Equation (Conservation of energy): The principle of energy conservation in liquid hydraulics is encapsulated in the Energy Equation, derived from Bernoulli's equation. This fundamental principle asserts that the total energy of the fluid within a pipeline remains constant at any specific point. It extends from the broader concept of energy conservation,

which holds that energy transforms from one form to another without being created or destroyed. The energy balance for fluid flowing between two points (A and B) under steady-state flow conditions is defined by Bernoulli's equation 1.4, a fundamental equation in fluid mechanics from which many other equations are derived.

$$Z_A + \frac{P_A}{\gamma} + \frac{V_A^2}{2 \times g} = Z_B + \frac{P_B}{\gamma} + \frac{V_B^2}{2 \times g} + h_f \quad (1.4)$$

As the flow rate of the liquid increases, so does the velocity, potentially causing the flow to shift from laminar to turbulent, marked by the presence of eddies and disturbances. The Reynolds number, a crucial dimensionless parameter, plays a pivotal role in classifying the flow regime within pipelines. It quantifies the balance between inertial and viscous forces, defined by the following equation:

$$Re = \frac{D \times v \times \rho}{\mu} \quad (1.5)$$

As liquid travels through a pipeline, energy dissipates due to friction between the liquid and the pipe surface, along with interactions among the liquid molecules. This loss of energy manifests as a decrease in liquid pressure. Accordingly, the energy dissipated due to friction is reflected as pressure drop. This frictional energy loss, known as pipe friction loss, arises from the resistance encountered by the flowing fluid against the pipe walls. It is influenced by various factors, including the pipe diameter, pipe roughness, flow rate, viscosity, and density. Moreover, the frictional pressure drop varies with the Reynolds number, indicating the flow regime's significance. Changes in flow regimes result in higher energy dissipation due to pipe friction. In laminar flow, frictional energy loss is relatively minimal compared to turbulent flow. The friction factor in laminar flow depends solely on the Reynolds number, whereas in turbulent flow, it is affected by factors such as pipe diameter, internal roughness, and Reynolds number. The pressure drops due to friction over a given pipe length, denoted by the liquid head (h_f), can be calculated using the Darcy-Weisbach equation, as mentioned below:

$$h_f = f \times \frac{L \times v^2}{D \times 2 \times g} \quad (1.6)$$

The Moody chart is a tool for determining the friction factor, where it is plotted as a function of the Reynolds number (Re) and the relative roughness of the pipe, denoted as ϵ/D . Over the past six decades or more, scientists and engineers have conducted numerous experiments to establish correlations for calculating the Darcy friction factor. Among these, the Colebrook-White equation stands out as a reliable and widely used approach for

approximating the friction factor. Based on the flow type, it can be approximated using the following equations [140]:

$$f = \begin{cases} \frac{64}{Re}, & \text{for laminar flow} \\ \frac{1}{\sqrt{f}} = -2 \times \log \left(\frac{\epsilon}{3.7 \times D} + \frac{2.51}{Re \times \sqrt{f}} \right), & \text{for turbulent flow} \end{cases} \quad (1.7)$$

In laminar flow, although the friction factor decreases as the flow rate increases, there is still a corresponding increase in pressure drop with higher flow rates. Conversely, in turbulent flow, an increase in pipe roughness for a given diameter leads to a corresponding rise in the friction factor. As liquid traverses a pipeline, friction induces pressure loss. The initial pressure required at the pipeline's inlet, accounting for friction, elevation changes and back pressure, is pivotal in determining the energy needed for liquid transportation. Accounting for the temporal aspect provides the pump power (shaft) required to transport the liquid in kilowatts (kW) is calculated as follows:"

$$P = \frac{Q \times \gamma \times h_{pump}}{\eta} \quad (1.8)$$

3. Minor Losses: In long pipelines such as trunk lines, the predominant factor contributing to the total pressure drop is frictional pressure in the straight sections of the pipe. Conversely, valves and fittings have minimal impact on overall pressure drop along the pipeline. Minor losses occur due to the dissipation of energy resulting from abrupt changes in the direction or intensity of liquid velocity within the pipeline. These losses typically occur at locations such as pipe contractions, expansions, and bends, and at flow restrictions like gate valves and check valves. In long pipelines, losses from valves, bends, elbows, and fittings are often negligible and can be disregarded without significant error. However, in shorter pipelines such as terminal and station piping, pressure losses from valves and fittings can constitute a notable portion of the total pressure drop. Therefore, it is crucial to account for these losses in engineering calculations for shorter pipelines to ensure accuracy [119].

1.1.5.3 Material Science

Depending on the characteristics and properties of the pipeline product and the external environment (such as soil and water conditions), different pipeline materials can be utilized. Design criteria also factor in material properties, particularly the SMYS, which denotes the stress level at which the material undergoes plastic or permanent deformation. Steel materials are classified into various grades based on their SMYS, including A-25, A, B, X-42, X-46, X-52, X-56,

X-60, X-65, X-70, and X-80. The numerical values following "5LX" denote the SMYS values in thousands of pounds per square inch (psi). For example, a pipe labelled 5LX-65 indicates a minimum yield strength of 65,000 psi. For high-pressure pipelines, it's typically advisable to use higher-strength steel specifications or grades for manufacturing pipes and fittings. This choice is made to mitigate costs associated with lower-grade materials, which would otherwise require additional steel weight [136]. Similarly, ASME 16.34 addresses various aspects of pipeline valve specifications, including pressure-temperature ratings, tolerances, dimensions, tests, and more. It classifies materials into different classes such as 150, 300, 600, 900, 1500, 2500, and 4500, with working pressure contingent upon the temperature range. Moreover, it is to be ensured during pipeline mechanical design that the net stress, including internal/external stresses (due to thermal expansion, wind, soil loads, equipment loads, displacements, etc.) shall remain within the allowable limits mentioned in codes.

1.1.5.4 Pipeline System Components

Mainline Pipe

1. Corrosion Protection:

(A) Buried Piping:

- (a) The buried portion of the piping shall be protected against corrosion by a Corrosion Monitoring System (CMS) as per site requirements.
- (b) Cathodic protection must be implemented along the entire length of buried piping.
- (c) All materials in contact with fluid shall comply with NACE Standard MR-01-75 [126].
- (d) During the construction phase of the pipeline, Temporary Cathodic Protection (TCP) must be provided. The design life for the TCP system should be 2 years or until the pipeline installation.
- (e) The Permanent Cathodic Protection (PCP) system should have a design life of 30 years with a protective current density as per IS:8062 [40].
- (f) The PCP shall comprise a transformer rectifier unit, longline wire anode, junction boxes, reference electrodes, DC/decoupler for earthing connections, and associated cables.
- (g) An adequate number of Cathodic Protection Station (CPS) shall be provided, and their locations shall be selected to ensure that the entire pipeline is adequately protected.

- (h) All CPS, associated with SV and IPS, shall include means for data acquisition of various analogue and digital signals for remote monitoring, which shall be interfaced with the pipeline Supervisory Control and Data Acquisition (SCADA) through a local Remote Telemetry Unit (RTU).
 - (i) The PCP system shall be designed such that CPS and anode beds coincide with SV and IPS to utilize a common reliable power supply and SCADA system, as far as possible.
 - (j) Monitoring the onshore cathodic protection system effectiveness should be conducted by measuring potential at fixed test stations along the pipeline route and using permanently installed electrodes. Generally, excessive overprotection should be avoided.
 - (k) Polarisation coupons shall be placed every 5 km, and AC corrosion coupons shall be placed in areas prone to AC interference to monitor AC corrosion densities.
 - (l) Post-commissioning PCP surveys should be conducted to assess the coating integrity.
 - (m) A corrosion inhibitor dosing skid should be provided to inject corrosion inhibitor into the pipeline to prevent internal corrosion.
 - (n) The piping buried sections should be protected against external corrosion using a three-layer polyethylene coating.
 - (o) A suitable joint coating system, compatible with the primary coating system, shall be selected, such as epoxy primed heat shrink sleeves (HSS) compliant with ISO 21809-3 [95].
- (B) Above Ground Piping:
- (a) The above-ground sections of the pipeline and piping must be coated with appropriate anti-corrosive paint suitable for typical corrosive environments.
 - (b) Valves and above-ground pipes must undergo thorough blasting to attain a surface finish of SA 2.5 prior to painting.
 - (c) Pipe wall thickness calculations, incorporating a corrosion allowance for the mainline pipe, should be performed according to ASME B31.4 [23].

Post-commissioning, it is essential to conduct regular monitoring and maintenance activities to the system's integrity and effectiveness over its operational life. This involves regular monitoring activities to ensure that adequate protection potentials are achieved. Verifying that power sources operate within their temperature limits for the ambient conditions. Ensuring anodes are not driven at current densities above the design limits to prevent early anode depletion.

2. Valves:

- (a) Ball Valves: Primarily used for on-off service and not suitable for throttling applications. Ball and check valves, primarily employed for on-off service rather than throttling applications, must adhere to API 6FA/API 607 and API-6D [14, 10, 9] standards for fire-safe design.
 - (b) Globe Valves: Globe valves must conform to the design specifications outlined in BS 1873 [39].
 - (c) Thermal Safety Valves & Pressure Relief Valves: A pressure relief valve serves as a safety mechanism engineered to automatically release excess pressure from a system, safeguarding against potential damage or failure, while a thermal safety valve protects against overheating by opening and releasing fluid when temperatures exceed safe operating limits to prevent excessive stress on the piping due to thermal expansion. Relief valves shall be adequately supported to withstand the forces generated by high fluid velocities. Valves employed upstream or downstream of full-capacity Relief valves must be full port ball valves equipped with locking mechanisms.
 - (d) Underground Valves: All underground valves must have their drain, vent, stem, and greasing points extended above the ground level and fitted with isolation valves. Valves intended for underground applications should be of the fully welded body type.
 - (e) Other requirements: Additionally, all isolation valves for vents must be accompanied by a spectacle blind downstream of the valve. The valve bore diameter should correspond to the internal diameter of the connected pipe, and adequate stem sealing must be ensured. All valves, except check valves, should have the ability to be locked in either the fully open or fully closed position if required. Operating valves must be accessible from the skid or walkway. If direct access is not possible, access must be provided using ladders and platforms. The centreline of valve levers or handwheels shall be at an approachable elevation (typically not more than 1.2 meters from the grade or platform).
3. Flanges: To facilitate maintenance, a sufficient number of flanges should be provided in all piping systems, allowing for the disconnection of valves and equipment. Flanges and fittings must adhere to the standards specified in ASME B 16.5, ASME B 16.47, MSS SP 44, or their equivalents [19, 20, 116]. Butt welded fittings should meet the requirements of MSS-SP-75 or ASME B16.9 as appropriate [22, 115]. The material considered for both flanges and fittings should be carbon steel, selected based on the service conditions and compatibility with the pipeline material.

4. **Station Piping:** The design criteria for station piping encompass several key guidelines to ensure operational efficiency, safety, and compliance. This includes adherence to ASME B 31.4 standards for piping design, provision of corrosion allowance for above-ground piping, and optimization of piping routes to minimize distance while maintaining a consistent elevation where possible. Additionally, the installation of piping, supports, and valves shall be performed meticulously to prevent obstructions, hazards, or interference with equipment operation and maintenance, with clear access space and horizontal clearance requirements specified. Adequate overhead clearance for piping and walkways, along with measures to minimize fluid accumulation such as slope maintenance and provision of valve drains, are also crucial aspects of the design. Valve drains must be installed on equipment lacking self-draining capabilities, and appropriate slope maintenance is crucial for drain and blow-down lines. Buried piping within terminal areas must meet minimum cover requirements (typically 1.2m) to protect against external factors. Overall, adherence to these design criteria ensures the reliability, integrity, and longevity of station piping systems.
5. **Branch Pipeline Connection:** For branch pipeline connections, the use of flow tees is required for all connections $\geq 40\%$ of the diameter of the main pipeline. These flow tees must comply with the standards specified in ASME B16.9/MSS-SP-75 [22, 115]. Additionally, adequate support, guidance, or anchoring should be provided to all above-ground piping to minimize excessive vibration, deflection, or loads on connected equipment. Expansion provisions should typically include the use of bends, expansion loops, and offsets to accommodate thermal expansion effectively.
6. **Piping Bends:** For piping bends, the use of hot induction bends is preferred, especially in situations with space constraints or at stations. The bending radius should be maximized to match the route, but never less than three times the diameter. It's essential to ensure that the pipe thickness after bending remains equal to or greater than the specified line pipe thickness. Therefore, it's advisable to use a higher-class pipe for fabricating hot induction bends with a 6D radius. In cases where on-field cold bending is necessary, it should adhere to a minimum bend radius of 30D for pipe sizes up to 16 inches, and 40D for 18 inches and above [129].
7. **Other requirements:** Insulating joints are necessary for electrically isolating the buried pipeline from aboveground transitions at stations. Welding procedures must conform to API 1104 standard [8]. All butt welds on the main pipeline must undergo 100% radiographic inspection. Moreover, manual welding with X-ray/gamma-ray and manual UT inspection (preferably with recording systems) is required for production welds in hook-up piping, station piping, and tie-ins. The minimum burial depth for the buried portion of the

pipings is set at 1.2 meters, except for critical areas like river/rail crossings where deeper cover may be necessary depending on design safety factors to meet statutory requirements [129, 141]. Following installation of the pipeline in the ROU, the entire pipeline undergoes hydrostatic testing. The hydrostatic testing procedure involves the testing of the mainline pipe at 1.25 times its design pressure, with a test duration of 24 hours. Similarly, terminals and station facilities are tested for atleast 4 hours at 1.25 times the design pressure.

Station

1. **Instrumentation System:** The instrumentation system at stations encompasses various field instruments for monitoring process parameters such as pressure gauges, temperature/pressure/differential pressure transmitters, temperature elements, motorized valves, non-intrusive pig indicators, pump vibration systems, and winding temperature monitors. Intrinsically safe instruments are equipped with isolator barriers in the control panel. Additionally, the tank farm management system includes servo gauges, ultrasonic level transmitters, pressure transmitters, temperature elements, and a common interface unit with a monitor. Field-mounted panels or cabinets must adhere to a minimum degree of protection specified in IEC 60529, achieving at least an IP 65 rating [92]. Additionally, provisions for extended shelter or canopy should be made to facilitate operator maintenance during adverse weather conditions. All instrumentation items used in hazardous areas must be certified by international agencies like “Factory Mutual Global (FM)”, “Underwriters Laboratories Inc. (UL)”, or “British Approvals Service for Electrical Equipment in Flammable Atmospheres (BASEEFA)”. Moreover, they should atleast be suitable for operation in Zone 1, Gr. IIA/B, temperature class of T3. Control room-mounted cabinets should have a minimum IP rating of 42 as specified in [92]. Low-pressure trips at pump suction utilize pressure switch-based systems, while high-pressure trips at intermediate pump discharges employ pressure transmitter-based alarms for enhanced operational safety. Centrifugal pumps must adhere to API-610 standards, ensuring their reliability and performance [17]. Reciprocating pumps, on the other hand, should meet the criteria outlined in API 674, API 675, or API 676 [16, 15, 12]. The suction & discharge pressure gauges and transmitters should be provided to both types of pumps to ensure effective monitoring of their operational parameters.
2. **PLC & SCADA System (PSS):** At main stations, a comprehensive instrumentation system is integrated with PLC-based process control and monitoring systems and workstation systems to ensure safe and reliable plant operation. The station process PLC manages interlocks, control, and monitoring of station parameters, while safety PLC such as the

critical valves, fire detection system, firefighting system, gas detection system, emergency call points, and emergency shutdown valves are integrated. The safety controllers should meet SIL 2/3 rating standards, ensuring reliability in line with IEC 61508/IEC 61511 guidelines [89, 90]. Control rooms at all stations, except SV and IPS, are equipped with control and monitoring facilities, operator cum engineering workstations, process PLC systems, and safety PLC systems. PLC-based control systems are provided at pumping and receiving stations for process interlocks, shutdown logic, MOV operation, field instrument signal control and monitoring, and station monitoring and control. Flow and density meters are connected to flow computers, which interface with the main station PLC for monitoring and control.

SCADA systems are responsible for centralized supervision, control, and management of the pipeline, enabling the exchange of critical parameters with RTUs placed along the pipeline route [137]. Sectionalizing valves, strategically installed at isolated intermediate stations (SV and IPS) along the pipeline for meeting pipeline safety requirements, can be remotely operated from the SCADA system at main stations through RTUs located at these stations. Each RTU is equipped with a dedicated memory, processor, communication processors, power supply unit, and Input/Output cards, ensuring comprehensive functionality and self-sufficiency. The SCADA system monitors critical parameters and controls infrastructure operations. Leak Detection System (LDS) enhances operational safety and reliability by accurately detecting and locating leaks under various pipeline operating conditions. The leak detection system is designed to function accurately and reliably across various operational conditions of the pipeline, including static, transient, and shut-in operations. The system is designed with dual redundant PLCs and RTUs to ensure continuous operation and prevent single-mode failures. GPS time servers synchronize clocks across the network for precise timing and coordination.

3. **Electrical System:** The electrical system is crucial for the operational efficiency and safety of the pipeline infrastructure. Pumping stations, with their higher energy demands, require a complex electrical setup including high-voltage switchgear and VFD panels for mainline pumps. Other stations are equipped with low/medium-voltage switchgear with corresponding transformers of varying ratings. Essential components that are meticulously installed according to hazardous area classifications and approved standards include MOV Distribution Boards, indoor and outdoor lighting Distribution Boards, Emergency Diesel Generators, AC/DC UPS Systems, Earthing systems conforming to the latest edition of IS: 3043 [41], and Lightning Protection materials per IS-2309 [42]. Various types of cables (Signal, Power, and Control) along with Cable Trays and supporting structures are deployed, and sized according to operational and process area requirements. Separate cable

trays are provided for different cable groups, and a comprehensive earthing network is established for lighting protection, equipment, and instrumentation systems. Appropriate earthing arrangements are to be established according to relevant standards, employing galvanised iron strips and copper wires for instrumentation grounding. Enclosures for electrical equipment must be designed for use in Zone 1 areas, classified as Gas Group IIA/IIB, or based on the specific properties of the fluid to ensure stringent safety standards. High-voltage loads ($\geq 200\text{kW}$) are supplied from the 6.6kV or 11kV system, while low-voltage loads are fed from the 415V AC system. Critical instrumentation systems are powered by a dedicated 230V UPS system. Indoor panels meet IP 42 standards, while outdoor panels have IP 66 or Exd protection as per hazardous area classifications. VFD designs adhere to harmonic control requirements specified by IEEE 519, featuring characteristics such as high input line-side power factor, low load side harmonics, regenerative operation capability, soft start/stop, reduced shoot-through faults, high starting torque, low torque pulsations, and UPS power for VFD PLC to prevent blackouts and software issues [86]. All pumps and motors shall comply with the IEC 60034 standards for specific efficiency, which aids in reducing energy costs [93].

4. **Telecom System:** A dedicated Telecommunication system ensures effective control, management, and supervision of the pipeline, especially in areas not adequately covered by public telecommunication networks. An optical-fibre-based Telecom System (SDH/M-PLS) forms an integral part of the infrastructure, complemented by CCTV cameras with a network video recorder and video management system, as well as an EPABX system supporting both analogue and IP phones. The system includes built-in self-diagnostic and network management features, with dedicated Network Management Systems. Additionally, a WAN Router facilitates high-speed data connectivity between the main stations. CCTV Systems equipped with PTZ and Fixed Cameras are recommended at all stations, supported by their servers, as well as client workstations at manned dispatch/receiving stations to enhance surveillance and security measures.
5. **Sump Tanks & Pumping System (STPS):** At the receipt facility, sump tanks serve as a containment measure for draining the content of the inlet pipe in case of contamination. Each product has its dedicated sump tank, equipped with an individual pump to transfer the content either pumped back into the pipeline or loaded into a tanker truck for disposal, depending on the content's specifications. These pumps are compliant with API 610 standard [17]. Typically, two sump tanks are installed to collect drains from header drains, scraper traps barrel drains, and TSV relief, among others. Dispatch stations also feature sump tanks along with a pump for collecting slops from different points like header drains, scraper drains, and Pressure Safety Valve discharges. To ensure operational safety, sump

pumps are interlocked to halt operation if liquid levels in the respective sump tanks drop below a predefined threshold, with level transmitters installed to monitor sump levels accurately.

6. Tankages: The products to be dispatched at DS are stored in dedicated storage tanks at these locations. The construction of storage tanks at RS is based on batch size, interface absorption, and contingency sales volume. These storage tanks at RS will store the product to meet demand until the next batch arrives. The RS storage tanks are connected to existing product transfer pumps for further transfer to the tank truck loading gantry.
7. Basket Filter: The basket filter is used to filter the incoming product. The system includes two sets of filters arranged in a filter bank, designed to maintain the maximum throughput even when one set of filters is out of action (on standby). The differential pressure across the filters is monitored by the PLC system, which will trigger an alarm when high pressure is detected, indicating the need to switch to the standby filter.
8. Flow Meter: The flow meter is used to measure the product flow rate. The metering skid facilities operate as an independent unit connected to the PLC system, either directly or through a flow computer. A flow computer is provided to monitor and control the flow metering function. The metering unit consists of flow meters for measuring different products such as MS, HSD, and SKO, with pressure and temperature compensations in the flow calculations. A meter run is included for flow straightening, and isolation valves are provided. The flow computers will be interfaced with the station PLC to RTUs for telemetry/SCADA for central monitoring. The system includes automatic "K" factor or meter factor correction based on product density in the flow computers.
9. PIG Trap: Pigging operations will be conducted manually due to their infrequent nature. These operations will occur during key activities such as post-installation hydrostatic testing to fill and subsequently remove test water from the pipelines, post-hydrostatic testing and drying for pipeline commissioning, periodic dust or debris removal, and at approximately five-year intervals for pipeline condition checks using intelligent pigs. Scraper traps (launchers/ receivers) should be installed preferably at all stations except SV station. These pig traps, conforming to ASME B 31.4 standards, should have been constructed from materials compatible with the line pipe material and should have the capacity to accommodate various types of pigs, such as batch and intelligent pigs. The main barrel of the pig trap units should be at least two sizes larger than the pipeline. Scraper traps should feature Quick Opening End Closures with band lock or clamp ring arrangements, designed and fabricated per API 6H and ASME Section VIII, Div.1 standard [7, 21]. Stations should be equipped with permanent facilities, such as jib cranes and tray trolleys,

for loading and unloading pigs, and the traps will be accessible by walkways or roads for equipment movement. Non-intrusive pig signallers should be installed downstream of scraper launchers, and upstream of scraper receivers. These signallers will monitor the passage of scrapers for performing maintenance under operating pressure. These traps should have safety locking devices to prevent accidental opening under pressure, with doors mechanically interlocked with the mainline valve to prevent opening when valves are in an open state. Safety features for pig traps should include safety locking devices to prevent accidental opening under pressure and mechanical interlocks with mainline valves to avoid opening when valves are in the open state.

10. Pressure Control Valve (PCV): These valves are used to reduce the flow of incoming product to the required pressure for station operations. It should typically be globe-type, either single-seated or double-seated, with an integrally mounted electro-hydraulic actuator control system on the valve actuator. Depending on service requirements, other valve types such as butterfly, ball, rotary plug, angle, or three-way valves may also be selected. The valves should accommodate up to 150% of normal flow or 110% of maximum flow, whichever is higher. The flange rating, body rating, and facing should conform to the associated pipeline's piping class specification.
11. Fire & Protection System (FPS): The Fire Water Network is designed to protect all new and proposed installations in compliance with safety codes and standards. The system includes fire and gas detection with multisensory detectors, flame detectors, hydrogen detectors, hooters, beacons, manual call points, and open/point gas detectors. Fireproofing, as per API 2218, will be applied to protect equipment and instruments such as critical valves and safety-critical control assets located in fire zone areas [13]. The fire alarm panel will be microprocessor-based and addressable, and the fire detection system should be SIL 2/3 compliant. The fire controller should be integrated with the safety PLC via Modbus, allowing parameters to be monitored from workstations in the control room. Tripping and alarm signals should be hardwired to the safety PLC. The fire detection system should be connected to a CO2 or clean agent fire suppression system for automatic or manual flooding in control rooms, equipment rooms, and electrical areas. A field-mounted electrically operated siren with a minimum audible range of 1 km should be integrated with the fire detection system. Hydrocarbon detectors (point type and the open-path type) should be strategically placed to detect leakages. An audio-visual alarm should be installed in the control room to alert operators of critical events and to take immediate action accordingly.
12. Civil works: The layout of facilities should be meticulously planned to ensure convenient access for all equipment & associated piping operation and maintenance. Further, the

inter-distance between facilities should adhere to the minimum requirements as specified in the relevant codes and standards such as OISD 118 [130]. To facilitate operation, maintenance, and emergencies, sufficient roads and raceways should be provided. Platforms and crossovers should be strategically positioned to enable easy access during routine operations and maintenance activities. Equipment and valves necessitating periodic maintenance should be supported (including temporary pipe supports when necessary) so that their removal should cause minimal disruption. Foundations for piping and equipment, approach roads, and plot development should be constructed. Civil facilities include buildings, sheds, boundary walls, and drainage systems.

TABLE 1.3: Civil Facilities

Building	DS	RS	IPPS	IPS	SV
Control Room Building	✓	✓	✓		
Process Area	✓	✓	✓	✓	✓*
Main Pump House	✓		✓		
Sump Tanks	✓	✓	✓	✓	
Roads	✓	✓	✓	✓	✓
Boundary Walls	✓	✓	✓	✓	✓
Water Drainage	✓	✓	✓	✓	✓
Telecom Building	✓	✓	✓	✓	
Electrical Building	✓	✓	✓	✓*	✓**

*Basic Process Area with SV; **Common Building for Telecom & Electrical Equipments and Guard Room

Station isolation valves or sectionalizing valves should be buried and fitted with stem extensions, positioning the centerline of the wheel or power actuator above the finished ground level (about 1.0 m). These valves should be installed in reinforced concrete pits and filled with sand up to the valve's base/bottom.

13. Hazardous Area Classification: All electronic and electrical instruments and equipment should be selected to comply with the area classification requirements (IEC Zone 0 to 2, or a safe area). Instruments should typically have a minimum temperature classification of T3 unless specific area classification drawings demand more stringent requirements. certified Intrinsically Safe (Ex 'ia') equipment, compliant with IEC-60079-11 standard [91], should be preferred for hazardous areas. If intrinsically safe instruments/equipment are unavailable, Flameproof (Ex'd') options should be considered. All outdoor instruments should have a minimum weatherproof rating of IP 65.

1.1.5.5 Pipeline Route Selection

Pipeline routing stands as a critical activity in pipeline projects, exerting significant influence on various network aspects such as design, construction, operations, maintenance, and overall project costs. A comprehensive engineering survey, including soil investigation & resistivity analysis, should be conducted to mark the alignment on the ground and determine engineering specifications regarding crossing alignment and ground profile. After conducting a thorough reconnaissance survey of all viable alternative routes, the alignment will be finalized. In order to prioritize public safety, pipelines should steer away from areas such as densely populated regions, areas with significant human activity, urban limits, stone quarries, reserved forests, and national parks, wherever feasible. The selection of the ultimate route will consider several factors: (i) Accessibility, construction feasibility, operational ease, and maintenance convenience.; (ii) Environmental protection and preservation of others facilities & properties; (iii) Minimal interference with electrical infrastructure.; (iv) Avoid areas that are consistently waterlogged and marshy; (v) Steer clear of existing & potential mining sites.; (vi) Population density considerations. Numerous engineering factors influence determining the optimal route, including terrain, topography, location of maintenance facilities (such as SV stations, pigging stations, pumping stations), supply and delivery points, obstacles, design conditions, safety, reliability, capital costs, operating costs, maintenance costs, soil characteristics, as well as codes, standards, and regulations, play pivotal roles in determining the optimal route. Moreover, socioeconomic factors like population density, infrastructure, urban development, and social implications further impact pipeline routing decisions. The initial planning of the pipeline route requires a considerable input dataset for further refinement and modification. This data is gathered and evaluated using advanced tools and techniques including satellite imagery & mapping, Geographical Information System (GIS), detailed surveys, hydrological data concerning flooding and riverbed depth, information on land and soil, aerial surveys and photography, on-site inspections, and Environmental Impact Assessment (EIA) studies. Since this topic constitutes a separate area of research, this study focuses on route selection provided in the user input including terrain information like elevation profiles and safety design factors for each segment.

1.1.5.6 Pipeline Economics

In every pipeline investment project, it's imperative to conduct an economic analysis of the pipeline system. This analysis ensures procurement of the appropriate equipment and materials at a reasonable cost to deliver the required service effectively while generating a profitable income. Significant capital investment is necessary for the construction and maintenance of

pipelines and compressor stations. Hence, to reduce costs, optimizing PNC transportation processes becomes imperative. During development, substantial capital input is required, predominantly associated with two main components: the pipeline system and pumping stations. The pipeline cost is directly linked to its length and diameter, with expenses increasing proportionally with diameter. Conversely, pump station costs depend upon operating power, influenced by both suction and discharge pressures. Opting for smaller pipe diameters increases pressure drop, thereby demanding high-power pumps. Hence, achieving an optimal balance between pipeline and pump costs is vital for profit maximizing. Given the intricate cost dynamics, optimizing the pipeline network is essential. Designing and operating pipelines cost-effectively is imperative, ensuring transportation costs remain low enough to yield substantial returns on financial investments.

In conventional practice, expert engineers manually perform the design of pipeline networks, accounting for various factors like volume, terrain, environmental impact, technical constraints, and economic considerations. Software such as Pipeline Studio [163] aids in evaluating the manually input PNC models to assess technical feasibility. Subsequently, based on its output, performance parameters such as capital expenditure (CAPEX), operational expenditure (OPEX), tariffs, and carbon emissions are also envisaged. However, as sections and variables become more intricate, this manual trial-and-error method becomes increasingly laborious, iterative, and time-consuming for engineers to analyse and optimize [45]. Despite low operational costs, pipeline infrastructure demands significant capital investment for design, engineering, and construction, necessitating thorough techno-commercial feasibility studies [184]. It's important to recognize that constructing well-planned pipeline networks entails significant capital investment and has lasting implications for the entire supply chain. Given the long-term nature of pipeline investments, even minor enhancements in planning and design can yield substantial long-term savings. On the other side, an erroneous design decision could lead to prolonged economic and environmental repercussions across the entire supply chain. Hence, ensuring robust scientific methodologies to reinforce pipeline network design is imperative. Consequently, a system-based optimization framework, developed in the programming domain, is indispensable for flexibility in integrating constraints efficiently incorporating all relevant variables, and expediting the search for optimal solutions to achieve optimal costing, reduce carbon emissions, and streamline engineering design processes. This shift allows pipeline owners to make more informed investment decisions and streamline their pipeline networks more effectively.

1.1.5.7 Carbon-Emissions

In recent years, there has been an increasing emphasis on mitigating & controlling carbon emissions, capturing significant interest among researchers [178, 81]. The effects of climate change are increasingly apparent and are shaping government policies globally [114]. To incorporate the costs of carbon emissions into the design and operation of PNC, it is crucial to evaluate emissions throughout the entire lifecycle, spanning from manufacturing/construction to disposal. This comprehensive approach ensures a thorough understanding of the environmental impact associated with the pipeline's construction, operations and maintenance. In response to this challenge, [186, 82] have proposed various carbon emissions factors, encompassing the pipeline's lifecycle in PNC design considerations. As technology and methodologies evolve, carbon emission coefficients associated with pipeline production and operations are expected to decrease over time, in line with governmental forecasts. To reflect this changing landscape, there is a need to consider dynamic carbon emission factors. During the multi-horizon optimization of the PNC design, these factors will impact the objective function evaluation. By incorporating dynamic carbon emission considerations, the optimization process can better reflect evolving environmental goals and technological advancements, ensuring a more sustainable pipeline infrastructure in the future.

1.1.6 Motivation/Need for Research

For vast countries like India, pipelines are arteries of a nation and a valuable asset. It is the most efficient, uninterrupted, eco-friendly, and economical mode of transport. However, their installation and commissioning demand significant capital investment. Designing a pipeline network involves balancing two key factors: pipeline diameter and pumping requirements. The overall cost of pipe is influenced by pipeline length and diameter, while the pumping station cost depends upon the suction and discharge pressure. Achieving an optimal balance between pipeline and pumping station costs is essential to maximize profits or minimize expenses. Opting for a smaller pipeline diameter increases frictional losses, necessitating more pumping power and stations, thereby elevating both capital and operating costs. Conversely, constructing large-diameter pipelines might be less feasible than smaller ones with more pumping stations, particularly in areas with steep elevations, prompting a tradeoff between pipeline diameter and pumping stations. Currently, this tradeoff is typically determined through manual methods, relying on experience and trial-and-error, before verifying hydraulic feasibility using simulation software. However, this approach may result in the under or overdesign of the pipeline network.

TABLE 1.4: Pipeline Network Capacity Utilization

Existing Pipeline Network	Capacity	% Capacity Utilization
Crude	148 MMTPA	58.5%
Petroleum Product (PP)	106.4 MMTPA	55.6%
Natural Gas (NG)	342.8 MMSCMD	89.8%
Overall Utilization of Existing Pipeline Network		75.8%

Historically, petroleum companies have utilized heuristic techniques relying on human judgment and experience rather than established system-based optimization methods. This approach heavily relied on trial and error, resulting in prolonged timelines even for experienced engineers. The time consumption increases exponentially with the number of variables. However, the emergence of system-based optimization techniques has shown promising results in significantly reducing the overall cost of pipeline networks compared to conventional heuristic approaches. This systematic approach allows for the automated and structured search for potential solutions.

Beyond the aforementioned challenges, accurately predicting product demand growth for the markets associated with the pipeline receipt stations presents a significant challenge. This uncertainty makes it challenging to forecast the long-term capacity requirements of pipelines accurately. The change in product delivery volume over time requires the construction of a larger pipeline and/or more number of pumping stations, consequently leading to increased pipeline tariffs. This pattern leads to a higher idle capacity during the initial operational phase. The full utilization of this excess capacity in the future necessitates higher pipeline tariffs initially also to offset the significant capital costs involved. To address this challenge, this study proposes analysing optimal project phasing through multi-objective optimization. This approach aims to balance the immediate costs of overcapacity with the long-term benefits, ensuring more efficient and cost-effective pipeline infrastructure. Regulators are focused on minimizing unnecessary pipeline infrastructure to optimize tariff costs and enhance the efficiency of pipeline facilities. Notably, there is a significant disparity between the actual product consumption recorded by the Ministry of Statistics [125] and the estimated demand provided by PPAC [145]. The Comptroller and Auditor General have highlighted similar findings, such as underutilized capacity in pipelines like Mundra Tundla and sections of the Panipat–Ambala–Jalandhar and Kandla–Bathinda pipelines, attributed to unmet projected product demand growth [44]. These challenges are evident across all types of pipeline networks in India, as mentioned below [146]:

In reality, certain pipeline projects have experienced significant underutilization, failing to generate the expected return on investment even after 17 years from their commissioning [143]. According to the Ministry of Finance’s report [58], there are plans for 17 gas pipeline projects worth Rs. 51,860 crores and 35 oil pipelines worth Rs. 52,278 crores in the next five years

(2020-25). This combined estimate of Rs. 1 Lakh Crore will account for 54% of the MOPNG total capital expenditure over the next five years. Given the substantial national capital involved in these new pipeline networks, there is a clear need for focused research aimed at developing better, system-based techniques for pipeline design optimization.

Regulators have a vested interest in optimizing pipeline infrastructure to prevent duplication among multiple suppliers, and unnecessary construction, and to minimize tariffs while ensuring efficient operation [142, 51]. Regulators, facing various social pressures, must simultaneously consider multiple impacts of a pipeline project. Moreover, the project needs to be economically viable to attract necessary investments. This multifaceted role of the regulator highlights the need for a multi-objective optimization tool to determine a new project's specifications. Therefore, this study focuses on optimizing key aspects of a new project, such as the pipeline tariff. Therefore, this research aims not only to achieve significant savings in the capital costs of pipeline projects for owners but also to ensure optimal tariffs for end customers.

The aforementioned challenges motivate the necessity for research into designing pipeline networks through systematic techniques, aiming to:

- Provide more reliable network configuration for simulations and its practical implementation.
- Minimize both the CAPEX and OPEX of a project, thereby leading to optimal tariff rates.
- Mitigate the risk of capacity underutilization, ensuring efficient resource allocation and utilization throughout the pipeline's lifecycle.

The investment costs and operational expenses of pipeline networks are so significant that even minor improvements in design and operating conditions can result in substantial savings in both costs and carbon emissions. The primary goal of this research is to develop a systematic decision-support tool to aid design engineers, pipeline owners, and regulatory bodies in optimizing PNCs. The goal is to curtail overall costs, minimize tariffs, and mitigate carbon emissions. Furthermore, the proposed algorithm holds potential for adaptation to other applications such as electric, roads, and water network design, thereby extending its applicability and impact beyond the scope of pipeline infrastructure [149].

1.1.7 Research Objectives

The following objectives are proposed through this research work:

1. To design a Techno-Commercial Modelling of Pipeline Network
2. To select the optimal pipeline section diameters and number of pumping stations
3. To optimize a pipeline transportation tariff based on capital and operating cost

Parameters of the above-mentioned objectives will be derived from the supply-demand statement available in the public domain, previously published works, and codes & standards.

1.1.8 Research Methodology

This research aims to identify optimal pipeline attributes, taking into account regulatory requirements and terrain information. It is recognized that pipelines of comparable length and capacity can differ significantly in construction, operational, and maintenance costs depending on their geographical context. The PNC design process encompasses the following steps:

1. Define Constraints and Parameters:
 - (a) User Input: The user will provide various input factors based on the problem statement and site-specific conditions, such as the analysis period, length of pipeline sections, product volumes and their properties (viscosity, density, and vaporization pressure), injection and tap-off points, product temperature, rate of change, various costs including OPEX and tariff, pipe class and grade, etc. Since this framework is developed in a programming language, it allows the user to also alter default coefficients and factors. These include cost coefficients, commercial diameters, carbon coefficients, back pressure, tax rate, depreciation rates, compensation cost, maximum distance between intermediate stations, corrosion allowance, pipeline operational days, roughness, and more.
 - (b) Pipeline Terrain: By leveraging geographical terrain data of the pipeline route, parameters such as laying costs, thickness requirements, elevation changes, maintenance costs, number of SV stations, and suitable locations for IPS will be determined. This information is crucial for hydraulic model simulation and performance parameters calculations. Assessment of elevation differences relative to the mean sea level of the area will be conducted based on the terrain and ground profile.
2. Pipeline Modelling: Mathematical modelling is an effective tool for designing an optimal pipeline network. The algorithm will be formulated by using fundamental hydraulic equations under steady-state conditions, taking into account boundary conditions, constraints,

and variables such as pressure, flow rate, pipe thickness, length, and standard discrete diameter sizes. Formulation of cost factors associated with various pipe sizes, pumping stations, related facilities, and repair and maintenance expenses. Additionally, modelling carbon emissions based on factors such as pipe manufacturing, transportation, laying, and station-related emissions, including construction and pump operations.

3. **Nested Optimizers & Technical Feasibility:** The optimization process employs nested optimizers: the outer optimizer determines the location & number of pumping stations, while the inner optimizer, based on these locations, assigns the pipeline diameter to each section, resulting in a Pipeline Network Configuration (PNC). For each PNC generated, the algorithm evaluates hydraulic feasibility against boundary conditions including maximum and minimum pressure (based on pipe class, material, & product properties), pipe thickness (dependent on pressure rating, pipe material, diameter, & standard-based coefficients), and product velocity (function of flow rate). Only technically feasible PNCs are selected for objective function evaluation, while unfeasible configurations are rejected and alternative PNC is assigned till the algorithm termination.
4. **Objective Function Evaluation:** The objective function will be derived from the objective function consisting of various performance parameters, along with rigid boundary conditions. The goal is to identify an equilibrium point between pipe size and the number & locations of intermediate pumping stations. The objective function will be designed to minimize the performance parameter/fitness function such as the overall cost of the pipeline network, including both CAPEX and OPEX, ultimately leading to an optimal tariff rate for product transportation. The modelling and optimization programming be performed on Python software. The proposed pipeline design algorithm will perform iterative calculations on the Mathematical Model for each pipe section for selecting optimal Pipe Diameter and intermediate Pumping stations till the lowest CAPEX and OPEX of the overall pipeline network are achieved.
5. **Optimal Pipeline Transportation Tariff:** For the selected pipeline network, the algorithm will provide pipeline transportation tariff based on 12% ROI/Discount Factor (as per PNGRB) & other financial factors (such as depreciation, tax, PAT). Additionally, this research will be extended to include multi-objective functions, incorporating carbon emissions as one of the criteria alongside overall cost or tariff, to ensure sustainable and low-emission development.
6. **Multi-horizon Optimization:** Pipeline projects are long-term investments with forecasted demand volumes. To extend the research objective, a multi-horizon optimization framework is proposed, where the final PNC is phased over the period, involving the construction

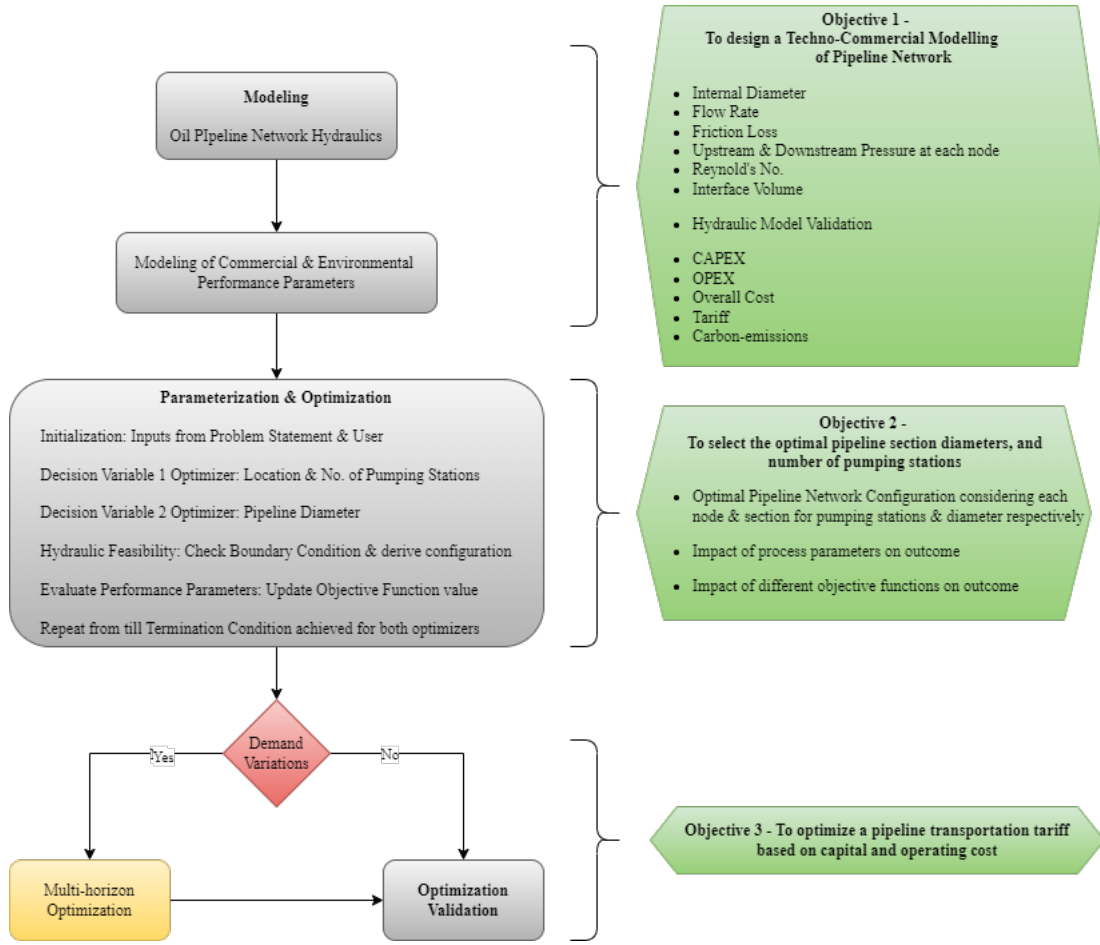


FIGURE 1.1: Research Methodology forPNC Design Optimization

of pumping stations, laying parallel pipelines in specific sections, or both. This approach not only enhances commercial-environmental performance parameters but also mitigates investment risk due to demand forecast uncertainty.

For confidentiality reasons, providing precise scenarios with exact demand, routes, and cost data is challenging. Therefore, information concerning pipeline capacity and indicative routes for modelling and implementing the proposed techniques will be sourced from publicly available documents. As the proposed framework primarily compares relative costs among different design alternatives, this study does not delve into evaluating exact cost values for materials, maintenance, and associated facilities.

Chapter 2

LITERATURE REVIEW

Rather than reinventing the wheel, it is crucial to reference prior research in related areas. This approach offers multiple benefits: it clarifies concepts, prevents redundant efforts, and identifies gaps between established knowledge and current understanding. The insights gained from reviewing these research articles and books should be documented in a tabular format to illustrate the progression of ideas related to the chosen topic. Identifying these gaps in the literature guided the formulation of untapped research areas, ensuring that the study addresses areas that need further exploration.

The literature review in this study offers a comprehensive survey of existing research in the domain of PNC optimization. Comprehending the pivotal factors that influence the design, optimization, and operation of pipeline networks is essential to ensure their effectiveness, safety, and sustainability. Over recent years, there has been a growing emphasis on optimizing PNC to enhance efficiency, cost-effectiveness, and environmental sustainability. Therefore, this literature review seeks to explore the theoretical foundations, methodological approaches, and practical insights derived from the industrial experience and prior research. By synthesizing and critically evaluating the existing literature, this review seeks to identify gaps, challenges, and opportunities for future investigation in the field. Furthermore, it establishes the groundwork for the subsequent chapters of this work, providing a robust theoretical foundation and context for the empirical analyses and contributions presented herein.

While the literature surveyed by [185, 110] extensively examines the merits and limitations of existing techniques and algorithms for Pipeline Network Configuration (PNC), the authors highlight a crucial point: even the most efficient algorithm may yield inaccurate results if essential modelling components are disregarded. Consequently, the feasibility of implementing these algorithms for real-world design challenges remains a topic of discussion. The main goal of the

TABLE 2.1: PNC Model Parameters

Author	Elevation Profile	Thermal Effect	Volume Change	Tankage	Eco. Velocity	Pump Eff. Factor	Minor Losses	Carbon-Emissions	CAPEX	OPEX	Cost Escalation	Tariff	Internal Diameter	SV/IPS	MHO
[45]	✓	✓							✓	✓			✓		
[103]	✓		✓			✓				✓			✓		
[160]									✓	✓			✓		
[169]						✓		✓		✓		✓			
[177]			✓						✓						✓
[180]			✓						✓						✓
[186]					✓			✓	✓	✓			✓		
[82]	✓	✓						✓							
[51]									✓	✓		✓	✓		✓
[149]			✓						✓				✓		
[80]									✓						
[60]		✓							✓	✓			✓		
[100]		✓				✓		✓		✓					
[170]									✓	✓	✓		✓		✓
[155]									✓	✓			✓		
[77]	✓							✓	✓	✓					
[43]	✓	✓	✓						✓	✓			✓		
[111]	✓	✓				✓		✓		✓		✓	✓		
[178]								✓	✓	✓					
[113]		✓	✓		✓				✓				✓		
[175]									✓	✓					
[36]		✓	✓						✓	✓			✓		
[108]			✓						✓	✓			✓		
[117]	✓		✓		✓				✓				✓		
[109]	✓					✓				✓					
[109]	✓					✓				✓					
[168]	✓								✓				✓		
[35]	✓								✓						
[166]		✓	✓		✓				✓	✓			✓		
[176]	✓								✓	✓			✓		
[104]	✓	✓				✓				✓			✓		
[26]	✓	✓			✓	✓				✓			✓		

proposed study is not to reassess the effectiveness of these techniques, but rather to highlight the technical & commercial variables missed in current literature on PNC modelling. Moreover, the research endeavours to conduct sensitivity analyses on performance parameters to offer a comprehensive understanding of the complexities involved.

The elevation profile of the pipeline route plays a crucial role in shaping the design and operation of PNC, affecting hydraulic feasibility, safety considerations, and cost implications [107]. However, it has been observed that many researchers have overlooked this critical factor in their efforts to simplify PNC modelling, as highlighted in Table 2.1. Similarly, many researchers have neglected the thermal impact on pipeline modelling, which not only affects its technical feasibility but also its performance parameters. This is especially critical considering that cross-country pipelines traverse diverse climatic regions—such as tropical, hilly, and desert areas. Furthermore, the PNC model should be able to handle variations in demand volume, which directly influence pump discharge pressure, operational costs, and carbon emissions. Despite its importance, the existing literature has paid limited attention to dynamic demand volumes and their effect on pump efficiency [103, 184, 148, 172, 131]. Remarkably, none of the authors have discussed the necessity of tankages and the importance of intermediate non-pumping stations like Sectionalizing Valve Stations (SV) and Intermediate Pigging Stations (IPS), which are crucial for ensuring pipeline operations and safety. Additionally, minor losses in pipeline systems have often been disregarded in the literature. During the comprehensive literature review, it is found that only few authors have discussed the importance of upper and lower velocity bounds, which are essential for maintaining pipeline stability and ensuring commercial viability [185, 186, 166, 148, 113, 117, 68, 26, 38].

Previous research in financial modelling has not sufficiently addressed the financial components outlined in the proposed work. As depicted in Table 2.1, numerous prior studies have overlooked operating expenses in their financial models for PNC design. Moreover, only a limited number of authors have taken into account the effects of cost escalation and discount factors in their models [34, 99, 170, 148, 152, 172]. It's worth noting that the pipeline route significantly impacts the project's costs, particularly in terms of pipeline laying expenses, land & ROU compensation, and station land acquisition costs. However, to the best of the author's knowledge, no prior studies have considered the influence of land use on these cost components. These financial modelling variables play a pivotal role in determining the performance parameters and ultimately affect the outcome of PNC design optimization. Through a comprehensive examination of parameters used in industrial design practice, the proposed model has meticulously integrated them, presenting a novel approach to incorporating the impact of pipeline route land use on its cost components.

The computation of tariffs plays a dual role in the optimization of PNC. Firstly, it consolidates the overall project cost (CAPEX and OPEX), simplifying the multi-objective problem into a single objective and thus eliminating sub-optimal designs. Secondly, it takes into account the impact of volume growth rate, preventing the establishment of irrational tariff rates and avoiding undue burden on pipeline users. While the significance of pipeline tariffs in operations has been underscored by [51, 165], previous works have not integrated them into the PNC model. However, to our knowledge, the analysis of the optimization problem considering the role of regulatory agencies in representing public interest has yet to be explored. In this context, the primary novelty of this study lies in formulating an optimization problem that ensures the project aligns with various aspects of public interest overseen by regulatory authorities. Thus, by proposing the inclusion of pipeline tariffs as a performance parameter, this study ensures the effective fulfilment of the needs of the entire supply chain, from owners to end-users.

In recent years, numerous countries worldwide have escalated efforts to combat climate change and adopt sustainable practices [114]. The "Paris Agreement" sets the goal of limiting temperature rise to 1.5°C compared to pre-industrial levels, with subsequent Intergovernmental Panel on Climate Change reports emphasizing the urgency of achieving carbon neutrality by 2050 [111]. Consequently, there is increasing political attention on environmental and sustainability concerns, with countries increasingly aligning economic policies more closely with environmental objectives. Governments are scrutinizing the environmental impact of projects more closely and imposing carbon taxes on entities with significant emissions [114, 34, 169]. Pipeline transportation is widely acknowledged as the most environmentally friendly mode of transport [111]. Therefore, in developing a PNC, it is crucial not only to optimize financial aspects such as cost and tariffs but also to minimize environmental impact by considering it as a key performance parameter during optimization, ensuring sustainable development and efficient operations post-commissioning.

As mentioned previously, building a pipeline network requires substantial capital investment and has far-reaching effects on the entire supply chain, making it essential to optimize PNC design. PNC design optimization typically consists of three key elements: Decision Variables, Objective Function, and Optimization Methodology. Decision Variables are crucial, encompassing factors such as the internal diameter of the pipeline along with the number & placement of pumping stations, which inherently impact other variables discussed in the literature. While previous research has delved into these variables [100, 155, 51, 149, 43, 36, 108, 180, 168, 35, 160, 183, 1, 172, 61, 185, 68, 173, 80, 77, 177, 132, 74, 144, 98, 99, 161, 110, 184, 148, 38, 46, 34, 186], the full spectrum of commercially available pipeline diameters and thicknesses have not been thoroughly investigated. Furthermore, while it is essential in the industry, to our knowledge,

previous studies have not extensively examined the implications of integrating intermediate nodes such as Sectionalizing Valve (SV) stations and Intermediate Pigging Stations (IPS) into PNC design optimization. These intermediate nodes could potentially serve as viable locations for constructing intermediate pumping stations, providing an alternative to relying solely on intermediate receiving stations. This gap represents an unexplored opportunity to broaden the solution space, allowing optimizers to uncover more efficient and optimal solutions.

In traditional optimization scenarios, the primary focus has typically been on commercial performance metrics such as Pipeline CAPEX, OPEX, or both, often presented as either mono-objective functions [60, 155, 149, 108, 117, 109, 168, 35, 166, 176, 160, 168, 152, 99, 161, 1, 172, 61, 2, 185, 124, 68, 46, 165, 120, 67, 156, 169, 28] or multi-objective functions [100, 113, 36, 103, 132, 98, 184, 148, 111, 186], offers a more balanced approach to assessing the overall commercial aspects of pipeline projects and ensuring equitable tariff pricing for users or customers. With the increasing global consensus on the imperative to address carbon emissions as part of the broader initiative to combat climate change and transition towards sustainable solutions [114], several researchers [186, 111, 178, 180, 100, 34, 169, 111] have incorporated the evaluation of carbon emissions from PNC construction and operations as a performance parameter in neo-classical optimization approaches. However, none of the previous works have proposed dynamic carbon emission factors that vary over time and ultimately influence the objective function during multi-horizon PNC design optimization. It's worth noting that carbon emissions and tariffs not only have distinct and significant impacts but also exhibit notable variations in their outcome values. For the first time, a multi-objective function will evaluate environmental and commercial performance parameters concurrently. This ensures that pipeline projects are not only commercially viable but also environmentally sustainable and socially responsible, leading to long-term benefits for all stakeholders involved.

Over time, pipeline owners and designers have developed practical techniques for designing pipeline networks. Traditionally, engineers have relied on experience, often employing a trial-and-error approach, taking into account factors such as route, terrain, volume, environmental considerations, technical constraints, and economic factors. However, as complexity increases with more sections and variables, finding optimal solutions becomes increasingly challenging, potentially resulting in suboptimal outcomes [60, 80, 51]. Over time, pipeline owners and designers have honed practical techniques for designing pipeline networks. Traditionally, engineers have relied on experience, often employing a trial-and-error approach, taking into account factors such as route, terrain, volume, environmental considerations, technical constraints, and economic viability. However, as complexity increases with more sections and variables, finding optimal solutions becomes increasingly challenging, potentially resulting in suboptimal outcomes

[60, 80, 51]. Therefore, it's crucial to ensure that the optimization of pipeline network design is supported by appropriate scientific methods. Various system-based optimization methodologies have been introduced in the literature to address this challenge. These methodologies aim to reduce costs, enhance efficiency, and improve the overall quality and reliability of the design process. By simultaneously considering all relevant dynamic variables, these methodologies substantially reduced the computation time required for PNC design optimization from several days or hours to just a few minutes. This capability allows designers to explore a broader range of solutions and minimize investment [80, 124, 133]. Typically, these methodologies involve optimizers that identify the most optimal PNC to achieve the desired state for a given problem statement while satisfying hydraulic constraints and objective function requirements. By leveraging such methodologies, pipeline owners can make well-informed investment decisions and operate their pipeline networks with greater efficiency and effectiveness.

Many applications across various fields can be framed as complex optimization problems, requiring models that accurately represent industrial systems. These models often become increasingly sophisticated, resulting in higher complexity and greater challenges in finding solutions. This complexity primarily stems from the nature of the functions and variables involved in the optimization process. These functions are often not only nonlinear but also frequently non-convex, which poses a significant challenge in typical minimization scenarios. Moreover, for constrained problems, determining the feasible space becomes exceptionally challenging. In engineering problems, where variables involve both continuous and discrete components, leading to discontinuities in the objective function and search space, known as mixed-integer problems. The addition of discrete variables introduces a substantial combinatorial complexity, especially in Multi Integer Non-Linear Programming (MINLP) problems, for which no polynomial-time algorithm is currently available. Given that industrial-scale problems may involve thousands of variables and constraints, computational times can become excessively long, potentially rendering the conventional analysis impractical [164]. This complexity typically arises on PNC design optimization when integer decision variables are introduced, particularly in cases where decisions involve discrete choices, such as selecting the node for installing a pumping station. Consequently, formulating the PNC optimization problem with binary variables to represent these discrete choices results in an MINLP problem. Among the numerous optimization techniques, two prominent classes stand out: deterministic methods and stochastic methods. Deterministic methods involve analysing mathematical properties of the objective function and constraints, such as continuity or differentiability, which enable these methods to provide optimal solutions. Noteworthy deterministic methods include the the Branch & Bound Algorithm (BBA) [80, 170, 177, 176, 24, 184, 164, 45], Branch-And-Reduce Optimization Navigator (BARON) [77], Branch-Refine-Optimize Algorithm (BROA) [43], Gradient Projection

Method (GPM) [132], Powell Directional Acceleration Method (PDAM) [74], Heuristic Deep Search Method (HDSM) [74], Generalized Reduced Gradient (GRG) [160, 2, 184, 28], Dynamic Programming Algorithm (DPA) [109, 24, 38], TurboMatch [34], and For+While Method [165]. Conversely, stochastic methods, also known as metaheuristics, rely on evaluating the objective function at various points in the search space selected based on heuristic strategies. Examples include Ant Colony Optimization (ACO) [28, 46, 25, 26, 104, 168, 80], Genetic Algorithm (GA) [28, 156, 173, 68, 124, 110, 185, 172, 1, 161, 99, 155, 60], Non-Dominated Sorting Genetic Algorithm (NSGA) [100], ϵ -Constraint Method (ECM) [148, 186, 51], Particle Swarm Optimization (PSO) [111, 110, 166, 35, 113], Chance-Constrained Programming (CCP) [36], Artificial Immune System (AIS) [149], Simulated Annealing (SA) [117, 110], Elitist Non-dominated Sorting Method and Self-adapting Differential Evolution (saDE) Algorithm (NS-saDEA) [98], Rank Optimization [152]. Metaheuristic approaches offer several advantages for solving MINLP problems compared to other optimization techniques. These algorithms are versatile and adaptable to various problem domains without requiring specific structures or assumptions. They excel in exploring large solution spaces, especially in high-dimensional optimization problems, where deterministic methods might struggle due to their reliance on explicit mathematical formulations. Stochastic algorithms efficiently explore the search space, increasing the likelihood of finding a global optimum or near-optimal solution. They can be parallelized to exploit modern computing architectures efficiently, enhancing scalability and performance. Moreover, stochastic is robust to noise, uncertainties, and changes in problem parameters, producing satisfactory solutions even in the presence of inaccuracies. Not relying on gradient information, they handle non-differentiable and discontinuous objective functions common in real-world problems. Additionally, stochastic excels in combinatorial optimization, efficiently navigating discrete solution spaces. Their ease of implementation and minimal problem-specific modifications make them accessible to practitioners without deep optimization expertise. Overall, the combination of flexibility, global optimization capabilities, scalability, and robustness makes stochastic approaches effective for handling MINLP problems more effectively.

The Single Horizon Optimization approach is typically used when demand volume remains constant, and there's no phasing in PNC construction. However, demand variability is inevitable and crucial for PNC design, construction, and operations optimization [103, 185, 51, 148, 131]. This is addressed by Multi-Horizon Optimization, where factors like dynamic pump efficiency, inflation rates, and carbon emission changes vary [157]. Moreover, handling demand variation requires consideration of its uncertain and estimated variations. Various approaches exist to address demand uncertainty in PNC design optimization. [173] reviewed various approaches for managing demand uncertainty in PNC design optimization, including scenario-based robust optimization methods. However, assigning probabilities to each scenario can be challenging and

subjective, potentially leading to inaccurate outcomes. [36] proposed design strategies to mitigate volume uncertainty, such as selecting larger diameters and incorporating safety margins in operating pressure design. They emphasized the trade-off between pipeline robustness and cost-effectiveness in handling demand volume uncertainty. [117] suggested that for uncertain volumes with temporary demand surges, it's preferable to incorporate margin provisions rather than phase the PNC, like constructing additional pumping stations. [120] recommended building extra storage tank capacity to accommodate contingency sales. These design margins for demand volume uncertainties are integrated into the PNC model proposed in this study. [165] proposed considering external dosing of drag-reducing agent additives to provide additional pipeline capacity margin. For estimated demand, [180] notified against solely relying on merely design margin provisions, as it could lead to overdesign, especially for long-distance pipelines with significant flow rate variations due to demand changes. Therefore, a balance between design margins and phased PNC construction is crucial for handling minor demand uncertainty, ensuring both financial viability and network transportation reliability.

Several authors studied the impact of estimated volume variation on pipeline diameter and thickness selection during design [166, 108, 2]. [180, 24, 165] suggested phasing the laying of parallel pipelines across the mainline during the project's time horizon. Similarly, [177] investigated pipeline network extension to additional demand nodes in a phased manner. [170, 99, 149] proposed multi-phase pipeline project phasing across a multi-horizon period, considering both laying new pipelines and constructing new pumping stations. However, these studies did not explore other intermediate stations as potential nodes for pumping stations, affecting overall optimization. This study elaborates on multi-phase optimization methods to address estimated demand variation, aligning with industry practices in pipeline project phasing.

The impact of various essential aspects of optimization frameworks is summarized below:

TABLE 2.3: Gap Analysis Summary Table

S.No.	Optimization Framework	Gap Analysis
1	Problem Statement/ Model: (Decision Variables & Performance Parameters)	1. In multiproduct pipelines, the mitigation of interface issues and the corresponding calculation for additional tankage are neglected, impacting both commercial and environmental outcomes 2. Terrain information, such as elevation and safety factors, is not considered, thus rendering the technical feasibility of the outcome debatable. 3. Internal diameter and thickness are not defined, resulting in inaccurate hydraulic outcomes. 4. Limited range of commercial diameters is considered for design, resulting in sub-optimal solutions. 5. The impact of parameter variations (such as temperature and volume) is not considered, making the technical feasibility of the outcome debatable.
2	Objective Function: 2.1 Cost (CAPEX & OPEX) 2.2 Pipeline Tariff 2.3 Carbon Emission (CE)	CAPEX & OPEX components not considered in literature such as: 1. Pipeline Linefill Cost & RS Tankages 2. SV & IPS Station Cost 3. Fixed CAPEX Cost The significance of IRR-based tariff is highlighted in the literature, but it has not been modelled. Modeled but not considered for PNC optimization, including Pipeline Laying CE and dynamic coefficients.
3	Methodology & Algo.: 3.1 SHO & MHO	1. Interdependence of variables not considered - the impact of intermediate pumping station location on change of diameter consideration. 2. The potential of SV/IPS locations as intermediate pumping stations is not taken into account.

Conclusion: The incorrect model and objective functions mentioned in S.No. 1 and 2 lead to unreliable results.

Chapter 3

TECHNICAL, COMMERCIAL AND ENVIRONMENT MODELLING

3.1 Technical Model - Pipeline Network Configuration

A pipeline network plays a crucial role in facilitating the movement of products from their source to their intended destinations, aligning with projected market needs within defined time-frames. These networks differ in structure and can be classified by their topology, including linear, branched, or cyclic configurations [151, 27]. The optimization process utilizes mathematical methods to navigate through the extensive solution space of decision variables and determine the combination of variables that results in the most optimal design for the pipeline network, based on the performance parameter(s) selected in the objective function. However, pipeline modelling presents unique challenges compared to conventional problems, as it encompasses various components such as pipeline length, diameter, thickness, material type, surface roughness, temperature variations, distances between pumping stations, and a complex set of nonlinear constraints involving both discrete and continuous variables [24, 100, 161].

Technical modelling involves formulation PNC decision variables, that is as diameter, as well as the number and location of pumping stations, to meet pipeline hydraulics, regulatory requirements, and other constraints. These fundamental equations are governed by physical constraints like energy and mass balance, hydraulic boundaries such as maximum allowable pressure, minimum pipeline thickness, and other regulatory constraints. Financial constraints, including the

desired internal rate of return, are also crucial. As a result, physical variables such as flow rate, line fill, tankage requirements, and pump power are directly or indirectly influenced by these conflicting requirements. The interaction and interplay of these components collectively form the mathematical representation of the PNC design problem.

To simplify the understanding of the hydraulic model, a linear PNC is considered, as illustrated in Figure 3.1. This network consists of a series of sections numbered ‘ n ’. After the establishment of a referred mathematical model, it can be easily extended to a tree topology by treating the branch node pressure as the sum of the minimum back pressure needed to prevent product vaporization and the dispatch pressure required to meet the demand in the connected branch line [24].

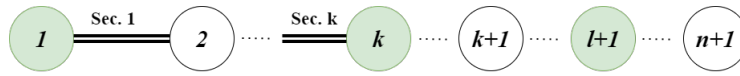


FIGURE 3.1: General Pipeline Network.

The potential number of configurations (PC) for the PNC design can be determined using the following equation, based on the decision variables of the number of intermediate pumping stations (Ps), the sections available for diameter change (Ds), and the number of commercial diameters (Cd) considered:

$$PC = (Ps + 1) \times Cd^{Ds} \quad (3.1)$$

The above analysis demonstrates that finding a solution using the trial-and-error method is remarkably time-consuming and labour-intensive, with complexity increasing exponentially as the PNC grows with more sections and variables, or even by adding more intermediate pumping stations. Instead of evaluating PNC design solutions as described in the aforementioned equation, which may take many days using the trial-and-error method, the proposed model optimizes the configuration in minutes, even when considering a wide range of commercial diameters. Therefore, a system-based tool is essential to calculate the hydraulics by formulating a mathematical model of the pipeline network and ultimately suggesting its optimal configuration by optimization frameworks for the given problem statement. As the pipeline networks continue to expand, this tool will become invaluable to the midstream oil and gas industry.

3.1.1 Pipeline Thickness

API 5L [11] specifies over thirty diameters with their respective standard thicknesses for pipeline design. However, previous studies often considered only a limited set of these diameters, restricting the solution space. Similarly, various pressure classes for steel pipes and flange fittings are defined in pipeline standard ASME 16.34 [18], which limits the internal pressure (P_I) in the pipeline. In the proposed model, the maximum pump discharge pressure (P_D) is considered to be 95% of P_I , providing an additional safety margin and accounting for demand uncertainty [36]. Furthermore, pipeline material properties vary by grade and are specified in ASME 31.4 for liquid pipelines [23]. Commonly used steel pipe grades for pipeline networks range from X42 to X70 [36]. The allowable stress must be lower than the SMYS value to ensure the safe operation of the pipeline under different pipeline ROU locations. Equation (3.2) mentions the SMYS value for the k^{th} section.

$$S_k = F_k \times J \times SMYS \quad (3.2)$$

The factor F_k provides an additional safety margin based on the terrain information of the ROU location, as specified in design standards [23, 129]. This terrain information is crucial for designing a safe and efficient pipeline network, affecting not only pipeline hydraulics but also key performance parameters such as land compensation costs, pipeline laying expenses, and station land acquisition costs.

The pipeline thickness (t_k) is a critical factor that affects the internal diameter (D_k) and ultimately the hydraulic feasibility of the pipeline. The pipe thickness at the k^{th} node is mentioned below in equation (3.3):

$$t_k = \frac{P_I \times OD_k}{2 \times S_k} + CA \quad (3.3)$$

While various pipeline thicknesses and diameters are commercially available, adhering to specific thickness boundaries is essential to mitigate potential damage during transportation and handling, account for uncertain loading pressures, and enhance public safety [108]. Therefore, pipeline thickness must comply with both the minimum requirements set by regulatory bodies [129] and adhere to the diameter-to-thickness ratio specified in Equation (3.4) to ensure hydraulic feasibility and structural integrity.

$$t_k \geq \begin{cases} 5.56mm \\ 0.01 \times OD_k \end{cases} \quad (3.4)$$

The wall thickness design outlined is appropriate for metal temperatures ranging from -29°C to $+120^{\circ}\text{C}$. The internal design pressure should be equal to or greater than the maximum steady-state operating pressure, which includes static head pressure, friction loss pressure, and necessary back pressure.

As per the API 5L specification, the longitudinal joint factor (J) for pipes is considered to be 1, for the pipes that are longitudinal seam submerged arc welded, electric welded, seamless welded, or helical seam submerged arc welded [129].

Pipe thickness is inversely proportional to the Design Safety Factor, which varies based on the ROU location [129, 159] as outlined below:

TABLE 3.1: Design Safety Factor on different ROU

Category	Design Safety Factor
Pipeline on Bridges	0.50
Crossing Railroads	0.60
Class I – Deserted	0.72
Class II – Village	0.60
Class III – City	0.50
Class IV – Densely Populated	0.40

The Corrosion Allowance (CA) should account for the expected reduction in wall thickness caused by internal corrosion, which may occur due to the properties of the liquid hydrocarbon and other service conditions. This should be factored into the calculated thickness unless alternative measures are implemented to mitigate internal corrosion. The corrosion allowance encompasses provisions for threading & grooving, decomposition, and any additional increase in wall thickness implemented as protective measures [129]. Additionally, it's essential to verify that the selected thickness adheres to the diameter-to-thickness (D/t) ratio which should remain below hundred, preventing pipe damage during handling and transportation [129, 108]. The steel quantity required, based on the pipeline's thickness and internal diameter, is calculated using equation (3.5), which directly impacts both the pipeline costs and carbon emissions [166].

$$S_p = \frac{\pi}{4} \times \rho_s \times \sum_{i=1}^n (OD_i^2 - D_i^2) \times L_i \times 1000 \quad (3.5)$$

3.1.2 Product Velocity

The liquid pipeline product velocity is typically the average velocity derived from the pipe diameter and liquid flow rate. However, it's essential to recognize that the velocity at the pipe centreline may exceed this average, depending on whether the flow is turbulent or laminar. In liquid pipeline networks, the products are typically assumed to be incompressible, meaning their density remains constant despite pressure changes [119]. Consequently, the liquid velocity in the pipeline remains relatively constant regardless of pressure fluctuations. For the k^{th} node, this is represented in Equation (3.6):

$$v_k = \frac{Q_k}{(3.6 \times A_k \times \rho)} \quad (3.6)$$

Liquid velocity is a crucial variable since an increase in flow velocity can lead to pipeline material erosion and corrosion, reducing the pipeline's lifespan. Additionally, maintaining velocity above a certain threshold limit is important to ensure the financial viability of the pipeline project, as suggested in previous studies [113, 153]. The economical velocity for the k^{th} node is given by Equation (3.7)

$$v_{E_k} = 0.88 \times Q_k^{-0.16} \quad (3.7)$$

The boundary condition for flow velocity is then specified in Equation (3.8):

$$v_E \leq v_k \leq v_U \quad (3.8)$$

Using Equations (3.6), (3.7), and (3.8), the range of admissible diameters from the list of all available commercial diameters can be derived for a given sectional flow rate, significantly reducing the computation process [166, 43], as shown in Equation (3.9):

$$\sqrt{\frac{1.273 \times Q_k}{v_U}} \leq OD_k \leq \sqrt{\frac{1.273 \times Q_k}{v_E}} \quad (3.9)$$

3.1.3 Node Pressure

To ensure efficient fluid transportation through a pipeline, maintaining sufficient pressure is crucial to offset losses due to friction and elevation changes. Longer pipelines and higher flow rates lead to increased friction losses, demanding a proportional rise in liquid pressure at pumping stations. In systems reliant on gravity flow, where the movement is driven by varying elevations, pumps may not be necessary if the pipeline descends from a higher elevated hill storage tank to a lower delivery point. Nevertheless, the pipeline still necessitates design considerations

to withstand the pressure resulting from the static elevation difference. Typically, the total required pressure includes three main components: frictional head, elevation head, and delivery or backpressure at the terminal. It is crucial to maintain a minimum pressure above the liquid's vapour pressure at the operating temperature across the entire pipeline. For LPG, approximately 15 kg/cm^2 of minimum pressure is typically needed, whereas for refined products with low vapour pressure, as low as 3 kg/cm^2 may suffice. Thus, both delivery pressure and minimum pressure are critical factors to consider for pipeline transportation.

The proposed PNC model aims to transport a specified volume of product from the dispatch station (*DS*) to various intermediate nodes and the receiving station (*RS*) at node " $n+1$ " over a given time horizon. For practical design, the model incorporates the necessity of IPS and SV stations to ensure safer operation, which involves segmenting the pipeline between two intermediate stations [151]. SVs are strategically installed at least every 50 km and before steep elevation changes, either within the intermediate station or as dedicated SV stations [34, 2, 129]. Additionally, the distance between two pigging facilities is maintained within 150-200 km, taking into account factors such as site availability, the maximum travel distance of intelligent pigs, the quantity of muck generated, and the displacement-water batch/plug quantity. Due to limited process facilities at SV stations, the diameter of the subsequent section remains the same as the preceding section, significantly impacting PNC design. Besides the DS, intermediate pumping stations are installed to provide sufficient downstream pressure to overcome pressure loss and transport the demand volume to the receiving station within the desired upstream pressure limits. The location and number of these pumping stations are decision variables in the design optimization process. Co-locating intermediate pumping stations with other predetermined intermediate stations (RS, SV and IPS) can result in cost savings of up to four times and reduce carbon emissions by six times [186]. Hence, based on mandatory and receiving station locations limit the potential locations for intermediate pumping stations to a manageable number, rather than an infinite number of possible locations. A standalone intermediate pumping station is referred to as an Intermediate Pumping-cum-Pigging Station (IPPS), while one constructed with an intermediate receiving station is called an Intermediate Pumping-cum-Receiving Station (IPRS). Notably, if IPPS or IPRS replaces SV stations during the PNC design optimizer search, the subsequent section's diameter can be modified (increasing the number of decision variables for pipeline diameter). Therefore, the location and number of pumping stations also influence the pipeline diameter, making the design problem nonlinear and more complex.

To ensure efficient fluid transport through the pipeline, sufficient pressure must be provided to overcome losses. For nodes other than pumping stations, inlet and outlet pressure values are assumed to be equal, with any pressure loss in the upstream section managed by the preceding

pumping station. Consider two consecutive pumping stations at nodes “ k ” and “ l .” The pressure loss between these stations is handled by the prior station at node “ k .” The total pressure required at node “ k ” to overcome frictional drag, elevation differences, and maintain minimum backpressure up to node “ l ” is calculated using equation (3.10), derived from fluid mechanics principles commonly used in pipeline design [177, 119].

$$P_{D_k} = P_{B_l} + \sum_{i=k}^{l-1} (P_{E_i} + P_{F_i} + P_{M_i}) + \sum_{i=k}^l P_{A_j} \quad (3.10)$$

For determination of the pipeline flow rate, the following 3 basic steps to be followed:

1. The initialization module shall encompass the entire pipeline system configuration along with the steady-state hydraulic parameters.
2. Parameters for discharge and back pressure at all stations should be assigned, as per the MAOP, with a design margin or constraints of pumping facilities provided at pumping stations, as applicable. Consequently, the maximum possible flow shall be determined using flow equations. This computation will ascertain the pipeline capacity for the given conditions and provided facilities.
3. The maximum flow within each section for subsequent withdrawal points shall be evaluated using the aforementioned methodology. Likewise, the volume flow shall be computed from one section to another, taking into account input from other injection points until reaching the ultimate exit point.

Consider the i^{th} pipeline section, which constitutes a subset of the $l - k + 1$ sections between the k^{th} and l^{th} nodes. The elevation pressure P_{E_i} represents the change in potential energy of the fluid due to elevation differences between the starting and ending nodes of the section. The frictional or head loss P_{F_i} resulting from pipe wall resistance is calculated using Equation (3.11) at the i^{th} node. The summation in Equation (3.10) corresponds to the pressure required to overcome frictional drag, minor losses, and elevation differences from the k^{th} node up to the l^{th} node. Minor losses in a pipeline section P_{M_i} occur due to energy dissipation from abrupt changes in magnitude or direction of product velocities, such as pipe enlargements, contractions, bends, and restrictions [119, 158]. At the l^{th} node, the minimum back-pressure P_{B_l} is maintained above the liquid’s vapor pressure and as per user requirements to ensure system component longevity, and efficiency, and mitigate the risk of fires and explosions [119]. The friction pressure drop in

the i^{th} section (P_{F_i}) is described by the following equation:

$$P_{F_i} = \frac{f_i \times L_i \times v_i^2 \times \rho}{19.62 \times D_i} \quad (3.11)$$

The friction factor (f_i) depends on flow characteristics and pipe properties, with various estimation techniques available such as the AGA, Panhandle A, Panhandle B, Weymouth, and Colebrook's equations [45, 184, 144]. For liquid pipelines, Colebrook's White Equation is widely recommended due to its high accuracy [45, 184, 144].

The discrete pressure required at each node is calculated by fulfilling the pressure boundary condition specified in equation (3.12) below:

$$P_B \leq P_k \leq P_I \quad (3.12)$$

3.1.4 Dynamic Pump Efficiency

Recognizing the significant impact of pump power on operational expenses (OPEX) and carbon emissions, it's crucial to account for the dynamic efficiency factor (η_r), which varies with the product flow rate Q_{k_p} at a constant speed during the p^{th} period of the time horizon. The dynamic efficiency factor can be denoted as a second-degree polynomial [103], as depicted in Equation (3.13):

$$\eta_p = \frac{2 \times \eta_0}{Q_0} \times Q_{k_p} - \frac{\eta_0}{Q_0^2} \times Q_{k_p}^2 \quad (3.13)$$

Consequently, the pump power required at the k^{th} node can be determined using Equation (3.14):

$$P_{KW_{k_p}} = \frac{Q_{k_p} \times P_{D_k}}{3600 \times \eta_p} \quad (3.14)$$

3.1.5 Thermal Effect

Taking into account thermal conditions' influence on hydraulics is vital, especially for cross-country pipelines navigating diverse climates like tropical regions, hilly terrain, deserts, and beyond. Estimating the fluid temperature within the pipeline can be achieved using the Sukhov formula, which considers both ambient temperature and inlet temperature [110]. When factoring in soil temperature, the Sukhov formula proves invaluable for determining pipeline temperature, drawing from ambient/soil temperature and inlet temperature data. These thermal

conditions profoundly affect the physical properties of the product, including density and viscosity. Increased viscosities, for instance, raise the pressure required for liquid transport, thereby increasing the demand for horsepower.

As temperature and pressure do not alter mass but do affect volume, it follows that density fluctuates with temperature. Density and volume exhibit an inverse relationship, as density denotes mass per unit volume. Consequently, as temperature rises, the liquid volume expands while its density decreases and vice-versa. In the typical temperature range observed in closed liquid pipelines, the liquid density varies linearly with temperature. This relationship can be expressed by the following equation [119]:

$$\rho_\tau = \rho_{15} - \alpha \times (\tau - 15) \quad (3.15)$$

where ρ_T is the density at τ degree temperature; α is a linear constant depending upon the type of the liquid, determined by two sets of densities at different temperatures

The pipeline's thermal conditions significantly affect the physical properties of the product, including density and viscosity. The relationship between temperature and density exhibits a nearly linear correlation, contrasting with viscosity, which follows a non-linear trend [137]. It is assessed through the ASTM method [31] as mentioned below.

$$\begin{aligned} \log(\log(v + 0.7)) &= A - B \log(\tau) \\ B &= \frac{\log(\log(v_2 + 0.7)) - \log(\log(v_1 + 0.7))}{\log(\tau_1) - \log(\tau_2)}; \\ A &= B \log(\tau_1) + \log(\log(v_1 + 0.7)) \end{aligned} \quad (3.16)$$

where v is kinematic viscosity, τ is product temperature

The above equations establish a linear relationship in logarithmic space between the viscosity ($v + 0.7$) and the temperature variable τ . The coefficients A and B are derived from known viscosity values at their respective temperatures. Specifically, B represents the slope between two points (v_1, τ_1) and (v_2, τ_2) , while A calculates the intercept using the previously determined slope B and the logarithmic value associated with the point (v_1, τ_1) .

For precise computations, density and viscosity are recalibrated for each pipeline section, factoring in the fluid's temperature relative to its reference temperature. This approach enables the inclusion of thermal effects in the entire pipeline system. The viscosity of the liquid at a specific temperature in each pipeline section is determined using the ASTM Method, enabling a comprehensive assessment of thermal impacts across the pipeline network.

3.1.6 Elevation Impact

The liquid pressure, primarily due to frictional losses, in a straight pipeline generally decreases progressively from the point of entry/inlet to the final delivery point. Hence, in the cases where the pipeline features a flat elevation profile without variations between its ends, the inlet pressure experiences a uniform decline due to friction loss at a given flow rate. However, if the pipeline includes elevation changes, the pressure drop is influenced by both friction losses and the cumulative effect of pipeline elevations. As previously mentioned, maintaining a minimum pressure throughout the pipeline is essential, particularly when transporting liquids with high vapour pressure. This minimum pressure should exceed the liquid's vapour pressure at the operating temperature to prevent vaporization, which can lead to an undesirable two-phase flow unsuitable for pumps. Hence, it is essential to maintain adequate pressure above this minimum threshold at high elevation points or peaks along the pipeline route to ensure operational reliability.

3.1.7 Blended Fluids

Despite 70% of refined products flowing in multiproduct pipelines [106], few studies have delved into their operational dynamics and design optimization [186, 109, 158, 106]. In a multiproduct liquid pipeline, multiple refined products, sharing similar chemical similarities but differing in physical properties such as density, are simultaneously transported in batches through the same pipeline [148, 109]. Designing and operating a multiproduct pipeline pose greater challenges compared to single-product pipelines due to factors like variations in product properties, managing interfaces, product tracking and segregation, and operational complexities such as planning product batch delivery cycles, aspects often unnoticed in prior research. The mixing occurs at the boundary locations of the two products when they are sequentially introduced into the pipeline. The density of the resulting mixture when two or more liquids are homogeneously blended can be computed using the weighted average method, assuming the densities of individual liquids are measured at the same temperature. The Blended Index Method is utilized to ascertain the viscosity of the blended interface [119].

3.1.8 Tankage Requirement

Batch operation is common in many liquid refined product pipelines, where multiple products are transported simultaneously by dividing them into discrete batches. Calculating the line fill volume is crucial for the efficient management of batched pipelines. Turbulent flow is essential to minimize intermixing of batches during transport. At the pipeline's end RS, each product

is directed to its respective tank. While some degree of intermixing at the interfaces between batches is inevitable, the contaminated liquid is usually directed to an interface tank. The extent of contamination at the batch interface depends on factors like the physical properties of the batched products, Reynolds number, flow rate and batch length. The interface generated from multiproduct transportation is managed by blending it with the main product within regulatory limits [82, 122], or by transporting it to a nearby refinery for regeneration [109]. However, since refinery sites are typically distant from product consumption markets, blending proves to be the more sustainable and economical option in practice. Nevertheless, blending the interface necessitates a minimum main product, requiring tankages to be constructed at the RS for storage and mitigation. Furthermore, additional tankage capacity is essential to maintain product supply during pipeline shutdowns and as a contingency against demand fluctuations. The total tankage requirement for accommodating the interface volume, along with an additional safety margin SM_{IF} and contingency demand volume against demand fluctuation and/or pipeline shutdown, is determined using equation (3.17). Tankage construction is a pivotal project aspect affecting both investment and associated carbon emissions. The equations below provide the overall tankage capacity (TA) required for interface mitigation and dispatch station product storage.

$$\begin{aligned}
 TA &= SM_{D_S} \times D_S + 50 \times B_{IF} \times SM_{IF} \\
 &\times \begin{cases} \sqrt{\sum_{i=1}^n (11.75 \times Re_{x_i}^{-0.1} \times \sqrt{(D_i \times L_i \times 1000)} \times A_i^2)} \\ \text{for } Re_x > 2100 \\ \sqrt{\sum_{i=1}^n (18419.9 \times Re_{x_i}^{-0.9} \times \sqrt{(D_i \times L_i \times 1000)} \times A_i^2 \times \exp^{2.19 \times \sqrt{D_i}})} \\ \text{otherwise} \end{cases} \\
 \text{where } B_{IF} &= \begin{cases} 0, & \text{for single product pipeline} \\ 1, & \text{for multiproduct pipeline} \end{cases} \\
 &\& SM_{D_S} \geq 0, 1 > SM_{IF} > 0
 \end{aligned} \tag{3.17}$$

The required tankage steel quantity is evaluated by equation (3.18) mentioned below:

$$\begin{aligned}
 S_T &= \rho_s \times \frac{\pi}{4} \times \left((D_T^2 - (D_T^2 - 2 \times t_T)^2) \times H_T + 4 \times \left(\frac{D_T + 0.04}{\cos \theta_T} \right)^2 \right. \\
 &\quad \left. \times t_{RT} \times w_{AT} \times D_A \times t_{AT} + D_B^2 \times t_{BT} \right) + S_{TA}
 \end{aligned} \tag{3.18}$$

3.2 Performance Parameters

Transporting products through a pipeline requires a seamless integration of several components. Technical modelling entails creating a mathematical representation of the Pipeline Network Configuration (PNC) that ensures feasible pipeline hydraulics (e.g., maintaining operating pressure within the maximum allowable limit), adheres to design codes, meets regulatory requirements (e.g., minimum pipeline thickness), and satisfies other constraints. This process encompasses selecting the appropriate pipeline diameter and determining the optimal number & locations of pumping stations. Physical variables such as flow rate, linefill, tankage requirements, and pump power are directly or indirectly implicitly influenced by these conflicting requirements. Financial modelling, on the other hand, involves accurately determining the commercial aspects of the selected PNC, including capital expenditures (CAPEX), operational expenditures (OPEX), and tariffs. These factors are influenced by market conditions, tax policies, discount rates, project debt-to-equity ratios, depreciation rates, and other user inputs & government regulations. The involvement of multiple techno-commercial factors and constraints adds complexity to the overall modelling of the PNC performance parameters.

While a pipeline designer's primary concern is ensuring the technical feasibility of the considered PNC, including meeting hydraulic and regulatory requirements, it is crucial to recognize that multiple technically feasible solutions may exist for the same supply-demand scenario. Therefore, it is equally critical to evaluate and compare these potential solutions based on specific performance parameters, discussed in the following section. These parameters will aid in selecting the optimal technical solution, minimizing environmental impact, and reducing investment costs.

3.2.1 CAPEX

The financial outlay of a pipeline project encompasses two primary elements: the expenditure on pipeline procurement & installation and the construction expenses for stations. These costs are notably influenced by the pipeline's route, such as the expenses related to laying the pipeline, compensating affected parties, and acquiring land, which can exhibit significant variations contingent upon whether the pipeline traverses urban zones, industrial hubs, or other high-consequence areas. Hence, it becomes imperative to integrate a parameter capable of adjusting cost estimates according to the pipeline's trajectory. In this regard, the cost-impact factor (I_k) is introduced in the modelling, derived from the average design safety factor of each pipeline section (F_k), as a metric offering insight into the nature of land use along the ROU and its geographical

context. By incorporating this factor into the cost estimation framework, we enhance the precision of location-specific cost projections, thereby fostering informed decision-making and project planning.

$$I_i = \begin{cases} 0, & \text{for } DS \text{ node} \\ 0.72 \times F_i^{-1}, & \text{for all other nodes \& sections} \end{cases} \quad (3.19)$$

The major components of the CAPEX associated with the mainline pipeline are mentioned below:

1. Line pipe cost based on the type of pipe and total quantity (weight) in Tonnage.
2. The inland handling/transportation cost and mainline pipe costing cost. Three Layers of Polyethylene (3LPE) External coating on bare line pipes should be considered with coating thickness input from the user (typically 2.5 mm).
3. Pipeline Laying cost inclusive of transportation of pipes to ROW by laying contractor, HDD & crossing laying works, line materials, induction bends, isolation joints, barred tees, pipeline markers, warning tape and more.
4. Land Compensation & ROU Acquisition cost which is typically constitute 10% and 30% of the land cost. However, it is dependent on the type of ROU category – new ROU, existing ROU and parallel to road/highway.
5. Route Survey & Soil Investigation cost
6. Cathodic Protection System cost
7. SCADA & Telecom System cost based on system architecture. The SCADA system cost includes the infrastructure necessary for remote monitoring, operation, & control of the pipeline from a main station.

The overall mainline pipeline CAPEX (O_P) is defined in below equation:

$$O_P = C_{PC} \times \rho_s \times S_p \times (1 + C_{TNC}) + \sum_{i=1}^n ((C_{SR} + C_{CP} + C_{TEL} + (C_{LC} + C_{LAY}) \times I_i) \times L_i) \quad (3.20)$$

The pipeline networks consist of various stations, each serving distinct functions (SV, IPS, IPPS, RS, and DS), whose number and positioning are depended upon the viable PNC outcome. Due to more complex processes of DS, IPRS, and IPPS, the collective capital expenditure (CAPEX)

tends to be relatively higher compared to RS. The cost of tankage is exclusively accounted for in RS. Similarly, the CAPEX for IPS is typically lower than that of RS but higher than that of SV, attributable to the additional facilities such as the PIG trap unit. Major items considered at various stations are as below:

TABLE 3.2: Station Facilities

Equipment	DS	RS	IPPS	IPS	SV
Mainline Pumps***	✓		✓		
Booster Pumps***	✓		✓*		
HVAC System	✓		✓		
CI & DRA (CIDRA) Unit	✓		✓		
Flow Meters***	✓	✓	✓		
Basket Filters***	✓	✓	✓		
PCV	✓	✓	✓		
PIG Trap	✓	✓	✓	✓	
STPS***	✓	✓	✓	✓	
Telecom System****	✓	✓	✓	✓	✓
PSS	✓	✓	✓	✓**	✓**
FPS****	✓	✓	✓	✓	✓
Station Piping****	✓	✓	✓	✓	✓
Electrical & Instrumentation System (EI)****	✓	✓	✓	✓	✓
Civil Facilities & Works (CFW)****	✓	✓	✓	✓	✓
Tankages	✓	✓	✓*		

*Applicable for IPRS only; **RTU Units only; ***1 Working & 1 Standby Unit; ****Different facilities in each type of station

The CAPEX for constructing various types of stations are detailed below:

$$\begin{aligned}
 O_{PS} = & C_{DS} + C_{BP} \times P_{KW_1} + \sum_{i=1}^{n-1} B_{PS_i} \times \left(A_{PS-L} \times C_{PS-L} \times I_{i-1} + (C_{MLP} + C_{HVAC}) \right. \\
 & \times P_{KW_i} + C_{MFM} \times Q_i^{0.55} + C_{SPT} + C_{PS-M} + C_{PS-E} + C_{PS-I} + C_{PS-C} \\
 & \left. + C_{PS-F} \right)
 \end{aligned} \tag{3.21}$$

$$O_{RS} = C_{TC} \times S_T \times (1 + C_{AT}) + \sum_{i=2}^{n+1} B_{RS_i} \times (A_{RS-L} \times C_{RS-L} \times I_{i-1} + C_{MFM} \times Q_i^{0.55} + C_{SPT} + C_{RS-M} + C_{RS-E} + C_{RS-I} + C_{RS-C} + C_{RS-F}) \quad (3.22)$$

$$O_{IPS} = \sum_{i=2}^{n-1} B_{IPS_i} \times (A_{IPS-L} \times C_{IPS-L} \times I_{i-1} + C_{MFM} \times Q_i^{0.55} + C_{SPT} + C_{IPS-M} + C_{IPS-E} + C_{IPS-I} + C_{IPS-C} + C_{IPS-F}) \quad (3.23)$$

$$O_{SV} = \sum_{i=2}^{n-1} B_{SV_i} \times (A_{SV-L} \times C_{SV-L} \times I_{i-1} + C_{SPT} + C_{SV-M} + C_{SV-E} + C_{SV-I} + C_{SV-C} + C_{SV-F}) \quad (3.24)$$

The overall CAPEX of the all pipeline stations is mentioned in below equation:

$$O_S = O_{PS} + O_{RS} + O_{IPS} + O_{SV} \quad (3.25)$$

The costs related to engineering and construction management include both preliminary and detailed engineering design, as well as personnel expenses for supervising, managing & inspecting the installation & construction of pipelines, pump stations, and associated facilities. In recent times, with the imposition of more stringent environmental and regulatory standards, environmental and permitting costs have expanded to cover environmental impact assessments, studies, and mitigation measures. These expenses also extend to acquiring construction permits for various crossings like roads, railways, rivers, and streams, as well as permits for pollution prevention equipment at pump stations and tank farms. Additionally, project budgets include provisions for owner expenditures during construction and legal and regulatory expenses. Contingency funds are considered to address unexpected events and design alterations, such as rerouting pipelines to avoid environmentally sensitive areas and making unanticipated modifications to pump stations and facilities.

The proposed financial model incorporates various fixed CAPEX elements, including Engineering, Procurement, and Construction Management costs (C_{EPC}), Spare costs (C_{SP}), Environmental Impact Assessment (EIA) studies and mitigation costs (C_{EN}), Contingency cost (C_C), and

Start-up commissioning & Owner-expenses (C_{SO}). These components also serve as a buffer against uncertainties arising from social, environmental, political, reliability, & safety factors, although they may not directly affect PNCs but significantly influence the overall expenditure and, notably, the final tariff. Additionally, the model accounts for linefill costs, representing the expense of filling the pipeline volume with product immediately post-commissioning. This cost is dependent upon the pipeline volume and thus is a function of the PNC diameter decision variable, akin to RS tankages. Predicting inflation and discount factors poses challenges as their values are contingent upon various factors, including governmental policies. Financial risk analysis, a distinct research domain, delves into these complexities [154]. Given that pipeline projects are often executed in phases across multiple horizons, contingent upon demand volumes and their growth rates, the model incorporates considerations for project phasing (PH_p) and asset cost escalation (cpi_p). The overall CAPEX is thereby determined, factoring in these considerations, as mentioned in below equation:

$$\text{CAPEX} = \sum_{p=1}^N \frac{\text{CAPEX}_p}{(1 + df)^{p-1}} \text{ where,} \quad (3.26)$$

$$\begin{aligned} \text{CAPEX}_p = PH_p \times & \left((O_P + O_S) \times (1 + C_{SP} + C_{EP} + C_{EN}) \times (1 + C_{SO} \right. \\ & \left. + C_C + C_{SO} \times C_C) + C_{LF} \times \sum_{i=1}^n L_i \times A_i \right) \times (1 + cpi)^{p-1} \end{aligned}$$

3.2.2 OPEX

Pipeline and station maintenance is crucial for ensuring that the project infrastructure and multi-product petroleum pipeline operate at maximum efficiency and minimum cost, with minimal operational downtime. Additionally, a comprehensive maintenance program guarantees the safe operation of the system and ensures a continuous supply of multi-product petroleum to various customers. After the CAPEX is expended and the pipeline, pump stations, & other facilities are installed, annual operating & maintenance costs will be incurred. These recurring annual expenses will also cover general administrative costs, including payroll, rental & lease expenses, and other costs required for safe and effective pipeline operations.

Operational expenditure (OPEX) holds considerable significance in pipeline modelling, warranting focused attention. Enhancing the operational efficiency of the established pipeline systems constitutes a distinct research domain. While pipelines typically have significantly lower operating costs in comparison to alternative transportation modes, their OPEX remains a substantial

factor influencing pipeline economics. Therefore, addressing operational enhancements during the design phase itself becomes crucial, ensuring cost efficiency and sustained profitability in the long run. The Major OPEX components are as below:

1. Pipeline Maintenance: Regular inspections of pipelines are essential, and a comprehensive program should cover the following key elements: (1) ROU survey conducted through foot patrols or aerial surveys, (2) Security and safety assessments, coating defect inspections, intelligent pig surveys, etc., (3) Implementation and monitoring of pipeline integrity systems such as Cathodic Protection System.
2. Station Maintenance: Regular inspection of above-ground installations is vital to identify and address potential issues that could lead to downtime or unsafe operation. Equipment suppliers typically provide recommendations for inspection frequency, which should be followed and scheduled to align with other maintenance activities. Inspection and maintenance activities may include functional and diagnostic checks, as well as equipment overhaul according to manufacturer specifications. Equipment requiring maintenance includes valves and actuators, metering systems, filtering equipment, skids, pig traps, and pumps. Power consumption represents a significant component of operational expenditure. Main stations are staffed 24/7 with teams operating in shifts, while SV stations are unmanned and fully automated, with permanent safety guards. These stations are remotely monitored and controlled from a master control station.

$$O_E = C_{ODS} + \sum_{i=1}^{n+1} \left(B_{PS_i} \times (C_{PS-AE} + (C_{OPE} + C_{HVAC} \times C_{OHV}) \times P_{KW_i}) + B_{RS_i} \times C_{RS-AE} + B_{IPS_i} \times C_{IPS-AE} + B_{SV_i} \times C_{SV-AE} \right) \quad (3.27)$$

$$O_L = C_L \times \sum_{i=2}^{n+1} \left(B_{PS_i} \times A_{PS-L} + B_{RS_i} \times A_{RS-L} + B_{IPS_i} \times A_{IPS-L} + B_{SV_i} \times A_{SV-L} \right) \quad (3.28)$$

$$O_M = C_M \times (1 + C_{AD}) \times \sum_{i=1}^{n+1} \left(B_{PS_i} \times M_{PS} + B_{RS_i} \times M_{RS} + B_{IPS_i} \times M_{IPS} + B_{SV_i} \times M_{SV} \right) \quad (3.29)$$

$$OPEX_p = \left(O_E + O_L + O_M + C_{OM-S} \times O_S + C_{OM-P} \times (C_{PC} \times \rho_s \times S_p \times (1 + C_{TNC})) + C_{IN} \times (O_S + O_P - O_L) + \sum_{i=1}^n C_{OCP} \times L_i \right) \times (1 + op_E)^{p-1} \quad (3.30)$$

Predicting the OPEX escalation (op_E) is a more intricate task compared to that of CAPEX as it is influenced by diverse factors like energy expenses, manpower & administration costs, and maintenance requirements. These factors vary across projects and can be challenging to quantify accurately. Consequently, the escalation of OPEX should be customized to the owner's specifics and aligned with other parameters in the problem statement. However, it's crucial to validate this input parameter meticulously with regulatory bodies, as it holds the potential to substantially affect the other performance metrics. The present value of the total OPEX for the given PNC is evaluated by the equation (3.31) mentioned below:

$$OPEX = \sum_{p=1}^N \frac{OPEX_p}{(1 + df)^{p-1}} \quad (3.31)$$

such that $OPEX_p = 0$ for $PH_p \neq 0$
& till commissioning

3.2.3 Overall Cost

The pipeline project's Overall Cost (OC) encompasses all expenditures involved in its engineering, design, procurement, installation, commissioning, and operation & maintenance throughout its lifespan. Many researchers focusing on pipeline network design problems have taken into account this comprehensive cost. Equation (3.32) describes the computation of the present value of the overall cost:

$$OC = CAPEX + OPEX \quad (3.32)$$

3.2.4 Tariff

Pipeline owners typically prioritize maximizing revenue, often prompting PNC designers to focus on minimizing overall investment. However, it's equally crucial to ensure that the pipeline infrastructure benefits its users and end-customers, which is the primary responsibility of regulators. Therefore, alongside investment minimization, pipeline tariff consideration is essential during the PNC design process to ensure cost-effectiveness and all stakeholder's benefit. Merely

calculating CAPEX and OPEX for a pipeline project isn't sufficient for a balanced approach to determining PNC performance parameters. Considering the tariff as a performance parameter is equally important, ensuring optimal market product prices for end customers. Thus, tariff consideration is pivotal for meeting owner, user, and regulatory requirements. Various methods exist for determining pipeline tariffs. In the proposed model, a widely adopted cost-of-service method is employed to ensure a minimum desirable return from the project. In this method, a minimum discount rate yielding a net-zero NPV is evaluated.

Equation (3.33) computes mechanical asset depreciation in the p^{th} year, accounting for the asset's lifespan.

$$DE_{M_p} = \begin{cases} TC_M \times PH_p \times d_M + DE_{M_{p-1}} \\ \text{for } p^{th} \text{ year s.t. } PH_p \neq 0 \\ \\ TC_M \times PH_p - \sum_{l=p-1}^{N-1} DE_{M_l} \times d_M \\ \text{after } p^{th} \text{ year} \end{cases} \quad (3.33)$$

Similarly, depreciation is calculated for various other components, including the pipeline (DE_P), civil assets (DE_{C_p}), and plant and machinery (DE_{PM_p}). The depreciation value of assets in the p^{th} year is given by equation (3.34):

$$DE_p = DE_{M_p} + DE_{C_p} + DE_P + DE_{PM_p} \quad (3.34)$$

The investment is assumed to be fully funded by equity. The tariff (T) for the base year, along with the Profit Before Income Tax (PBIT) and tax on profit, is calculated using equations (3.35) and (3.36):

$$\begin{aligned} PBIT_p &= T \times V \times ((1 + ta_E) \times (1 + t_v))^{p-1} - CAPEX_p - OPEX_p \\ \text{such that } V &= 0, \text{ \& } OPEX_p = 0 \text{ for } PH_p \neq 0 \\ &\text{\& till commissioning} \end{aligned} \quad (3.35)$$

$$IT_p = \begin{cases} 0, \text{ for } (PBIT_p - DE_p) \leq 0 \\ (PBIT_p - DE_p) \times IT \\ \text{for } (PBIT_p - DE_p) > 0 \end{cases} \quad (3.36)$$

The discount rate at which $NPV = 0$ is called Internal Rate of Return (IRR), and equation (3.37) calculates the pipeline tariff for the desired IRR rate.

$$T = \frac{\sum_{p=1}^N \frac{CAPEX_p + OPEX_p + IT_p}{(1+irr)^{p-1}}}{\sum_{p=1}^N \frac{(V \times ((1+ta_E) \times (1+t_v))^{p-1})}{(1+irr)^{p-1}}} \quad (3.37)$$

The non-linear nature of equation (3.36) complicates the problem, requiring an iterative optimizer based on the Levenberg–Marquardt Algorithm for a solution [174]. This algorithm is known for its robustness in finding solutions, making it suitable for solving such complex problem statements [97].

3.2.5 Carbon-Emissions

As global consensus strengthens regarding the need to address carbon emissions as part of broader initiatives to combat climate change and promote sustainable solutions that benefit all stakeholders [114], extensive literature reviews have examined carbon emissions within the oil and gas sector [181, 47]. Several researchers, including [186, 111, 178, 180, 100, 34, 169, 111], have integrated carbon emissions from pipeline network design and operations as a performance metric in neoclassical optimization approaches. When assessing carbon emissions in a product pipeline, specific input variables hold more significance than others. According to [81], factors like pipe diameter, length, wall thickness, and demand volume carry substantial weight. Thus, it's crucial to meticulously evaluate these input variables when modelling a PNC.

With technological advancements and evolving methodologies, it is anticipated that pipeline carbon emissions will decrease in the future, aligning with governmental projections. To overcome the limitations of previous studies, the proposed PNC carbon-emission model in this research integrates time-dependent carbon emission factors [81]. While there's been a notable shift in road transportation towards electric vehicles, actual carbon emission reduction depends on transitioning to a clean energy mix [128]. Environmental assessments of pumping station operations, as seen in studies like [111, 77], highlight the potential to reduce carbon emissions by utilizing renewable energy sources for electricity consumption. The proposed model implicitly considers energy produced by renewable sources through dynamic electricity carbon emission factors, with its coefficient estimated to decrease by 33% by 2026 [121]. Similarly, dynamic factors for steel production carbon emissions are taken into account for pipeline and station installations beyond the initial phase [134]. The carbon footprint produced by the construction and operation of the station and pipeline are detailed in equations (3.38) and (3.39), respectively [186, 82, 76]:

The equation (3.38) provides a comprehensive view of the various sources of carbon emissions associated with the pipeline station's construction and operation, enabling a thorough assessment of its environmental impact over time. The total carbon emissions in the pipeline station, denoted as E_s , encompass several key components over the analysis period. First, carbon emissions from tankage construction represented as S_{T_p} for up to p years, are calculated using the Steel Carbon Emission Coefficient (C_{SCE}). This includes emissions from both the steel required for construction and road transportation of materials to the site, adjusted by the Road Transportation Carbon Emission Coefficient (C_{RD}) and total transport distance, accounting for both the manufacturing plant transport length (L_{MP}) and additional transportation lengths of each section (L_i). Second, emissions from pump operations are assessed by evaluating electricity consumption over the operational period (T_O), using the Electrical Carbon Emission Coefficient (C_{ECE}). These emissions are dynamically adjusted across the time horizon by incorporating time-dependent factors, γ_{SCE} and γ_{ECE} , which modify the respective emission coefficients for steel and electricity based on year p . Additionally, emissions from the construction of pumping stations are included, either exclusively (C_{N-PS}) or alongside emissions from the receipt station (C_{E-PS}). Finally, the equation accounts for emissions from fugitive hydrocarbons, represented as C_{FG} .

$$\begin{aligned}
 E_s = & \sum_{p=1}^N \left((C_{SCE} \times \gamma_{SCE}^{p-1} + C_{RD} \times (L_{MP} + 0.5 \times \sum_{i=1}^n L_i)) \times S_{T_p} + \right. \\
 & \sum_{i=1}^n (B_{PS_i} \times C_{ECE} \times T_O \times P_{KW_{i_p}} \times \gamma_{ECE}^{p-1} + (B_{IPPS_i} \times (C_{N-PS} + N \times C_{AX}) \\
 & \left. + B_{IPRS_i} \times C_{E-PS}) + C_{FG} \times V \times (1 + t_v)^{p-1} \right) \quad (3.38)
 \end{aligned}$$

The equation (3.39) encapsulates the multifaceted sources of carbon emissions linked to the main pipeline's construction and installation, providing a detailed framework for evaluating its environmental impact. The equation E_p represents the comprehensive assessment of carbon emissions generated from the main pipeline. Similar to the previous equation, E_p includes emissions stemming from the production and transportation of the steel required for the pipeline, denoted as S_{P_p} . Additionally, it accounts for carbon emissions resulting from soil erosion (C_{SE}) and ROU excavation (C_{SX}) that occur during the pipeline installation. These emissions are influenced by several factors, including the sectional length (L_i), diameter (D_i), coating width (w_C), trench width (b_T), and trench depth (h_{T_i}). Furthermore, excavator parameters, represented as $Ex_B, Ex_C, Ex_E, and Ex_{HP}$, along with the type of soil (C_{SOC}), play a critical role in

determining the overall carbon emissions associated with these activities.

$$E_p = \sum_{p=1}^N \left((C_{SCE} \times \gamma_{SCE}^{p-1} + C_{RD} \times (L_{MP} + 0.5 \times \sum_{i=1}^n L_i)) \times S_{P_p} + C_{SE} \times \sum_{i=1}^n L_i \times (D_i + w_C)^2 + \frac{C_{SX} \times \sum_{i=1}^n (L_i \times (D_i + w_C + b_T) \times h_{T_i})}{(141.5 \times Ex_B + 10.23 \times Ex_C + 290.73 \times Ex_E - 0.521 \times Ex_{HP} + C_{SOC})} \right) \quad (3.39)$$

The overall performance parameter for carbon emissions is mentioned below:

$$E = E_S + E_P \quad (3.40)$$

This study envisions the impact of incorporating dynamic carbon emission factors into the Carbon Emissions (CE) objective function on the outcome of multi-horizon optimization.

Chapter 4

PIPELINE NETWORK DESIGN OPTIMIZATION

A pipeline designer's main responsibility is to assess the technical feasibility of the proposed model, taking into account hydraulic and regulatory standards. Nevertheless, it's important to note that there could be several technically feasible solutions for the same supply-demand scenario. For instance, given a specific set of inputs such as demand and terrain, both large-diameter pipelines or small-diameter pipelines with additional pumping stations could be viable options. Thus, choosing the optimal PNC from several potential technical viable solutions requires optimizing trade-off parameters, that is the pipe diameter and the number & location of intermediate pumping stations, using objective functions. These objective functions are discussed in this section.

The optimization of a pipeline network design entails consideration of various components such as pipe diameter, required inlet & delivery pressures, line length, spacing between pumping stations, temperature, and delivery volume. Each of these components impacts the overall construction and operating costs to varying degrees. Due to the complexity and inter-dependency of these variables, identifying the optimal solution can be a challenging task, often necessitating the investigation of many options to ensure a robust solution. Pipeline engineers traditionally rely on their experience and judgment to assess pipeline configurations through the trial-and-error method before checking their hydraulic feasibility using simulation software [51]. However, this approach is iterative, complex, tedious, & time-consuming, and the chances of sub-optimal results increase with the complexity of the pipeline network [60, 80]. This may lead to overdesign or under-design of the pipeline network, especially if the design problem statement involves a demand growth rate [60]. To address this issue, various system-based optimization algorithms

have been proposed in the literature. These algorithms offer more precise pipeline cost reductions compared to the trial-and-error approach, significantly decreasing design computation time from hours or days to mere minutes, along with reducing overall investment costs [80, 124]. For instance, [80] found that system-based optimization of PNC could lead to savings of around 12% compared to the traditional trial-and-error method, which could go as high as 35% [133]. As discussed in previous sections, pipeline modelling and optimization design have gathered significant attention from the research community. Nevertheless, as emphasized in this study, the mathematical techno-commercial models and their associated objective functions in prior research oversimplified the complexities of practical design problems. Therefore, regardless of whether the most advanced optimizer is utilized in the previous works, the effectiveness of the outcomes for real-world design problems remains uncertain and is a subject of debate for practical implementation. In the proposed optimization framework, the PNC model incorporates variables such as temperature, elevation, dynamic pump efficiency factor, and constraints on velocity & thickness. The model also holistically considers all crucial commercial and environmental aspects of pipeline construction and operations. Moreover, for the first time, the proposed model has considered intermediate stations, such as SV and IPS, providing additional search space to the pumping station optimizer for potential pumping station nodes. An optimization framework has been developed along with computer programming to provide optimal solutions for PNC design for the rapid assessment considering all of these parameters on the optimal design.

A cross-country pipeline project typically encompasses three major stages: preconstruction activities, including design and feasibility studies; construction activities carried out at the site; and post-construction tasks such as inspection and commissioning. This study focuses specifically on the preconstruction phase of the pipeline project.

4.1 Optimization Constituents

The design optimization of PNC comprises three foremost components: Decision Variables, Objective Function, and Optimization Technique.

4.1.1 Interdependent Decision Variables & Expanded Search-Space

The Decision Variables should encompass the number & location of pumping stations along with the pipeline's internal diameter, as all other variables are dependent either explicitly or implicitly. These decision variables are not only intricately interlinked, but also there are trade-offs between them. While previous studies have considered them during the modelling [100,

155, 51, 149, 43, 36, 108, 96, 180, 168, 35, 160, 183, 1, 172, 61, 185, 68, 173, 80, 77, 177, 132, 74, 144, 98, 99, 161, 110, 184, 148, 38, 46, 34, 186], they often lack a comprehensive approach such as decision variables interdependence, consideration of SV & IPS for pumping stations and commercial discrete pipeline diameters. As highlighted in the literature review, the proposed framework enhances the optimization of PNC design by significantly expanding the scope of decision variables. This broadening inherently increases the complexity of the optimization problem, thereby expanding the potential for discovering superior solutions.

This framework expands its scope to consider the potential utilization of intermediate stations, specifically Sectionalizing Valves (SV) and Intermediate Pumping Stations (IPS), as worthwhile nodes for constructing intermediate pumping stations (in addition to intermediate receiving stations). However, it imposes a condition that the pipeline diameter in sections following the SV station node should remain unchanged relative to their preceding sections due to limited process facility. Conversely, if the SV station is transformed into an intermediate pumping station node during optimization, the set of applicable decision variables for the pipeline diameter will be altered, resulting in a complex relationship between the diameter decision variable and another decision variable that is the location of intermediate pumping stations selected by the optimizer. Therefore, these interrelated variables need to be addressed separately by individual nested optimizers using system-based optimization methodologies, as discussed in subsequent sections. To the best of the author's knowledge, no research paper has addressed the industry practice of subdividing pipeline sections and its impact on the selection of section diameter. This crucial aspect has not been addressed by any of the researchers in the existing literature.

Moreover, the proposed framework considers the pipeline diameters and thicknesses commercially available as per API 5L standards. Additionally, it introduces an innovative approach that utilizes the demand characteristics outlined in the problem statement and velocity constraints specified in the equation (3.8). This approach enables the selection of a range of technically and commercially feasible diameters for the l^{th} section during the optimization process, as elucidated in equation (3.9), ensuring the efficiency, effectiveness, and expedition in the optimization process.

4.1.2 Objective Function Formulation

Multiple feasible Pipeline Network Configurations (PNCs) can arise for a given problem statement, necessitating design decisions based on the objective function. While a linear algebraic approach can provide an ideally designed pipeline network by setting the derivative of its combined mathematical function to zero and solving for the variable, real-world scenarios present a

more complex nonlinear problem. This complexity involves boundary conditions and multiple conflicting variables, each influencing performance parameters to varying degrees while maintaining technical feasibility. Achieving the optimum solution becomes a tedious task, as the objective function (Z) represents a mathematical expression derived from a set of exclusive performance parameters, augmented with penalty functions to ensure both technical feasibility and commercial viability of the PNC solution, mathematically represented in the below equation.

$$\begin{aligned} \text{Minimize } Z &= \sum_{q=1}^v PP_q(x) \\ \text{subject to, } HC(x) &= 0 \end{aligned} \tag{4.1}$$

In the optimization process, $PP_1(x), PP_2(x), \dots, PP_v(x)$ denote the multiple fitness functions in an objective function to be optimized. If maximizing any of the fitness functions is required, they can be transformed into minimization problems by taking their inverses. The individual performance functions specified in equations (3.26), (3.31), (3.32), (3.37), and (3.40), either individually or in combination, are regarded as optimization objectives. The technical feasibility of the PNC model relies on adhering to the thickness, velocity, and pressure boundary conditions outlined in equations (3.4), (3.8), and (3.12), respectively. It's crucial to emphasize that these conditions must be met concurrently, and any deviation can lead to pipeline failure, with potential repercussions including environmental harm, casualties, and financial losses. To enforce compliance with these crucial boundary conditions, a hard constraint, denoted as $HC(x)$, is imposed.

4.1.3 Optimization Technique

In pipeline network design optimization, opting for a stochastic approach over a deterministic offers numerous advantages. Stochastic techniques are adept at navigating complex solution spaces with many variables including discrete variables, making them well-suited for the intricacies of pipeline design. They enable decision-makers to balance competing objectives and discover Pareto-optimal solutions effectively, particularly in multi-objective optimization scenarios. Moreover, stochastic algorithms exhibit flexibility, scalability, and robustness, enabling them to handle uncertainties, incorporate real-world constraints, and adapt to dynamic environments seamlessly. The effectiveness of stochastic methods in navigating vast solution spaces and discovering globally optimal or near-optimal solutions renders them a pragmatic option for tackling the intricacies of pipeline network design optimization. Considering the potential impact

of constraints related to the problem formulation, employing a stochastic approach is deemed suitable for this problem statement.

4.1.3.1 Genetic algorithms

Genetic algorithms (GA) are versatile search techniques inspired by principles from genetics and natural evolution. Genetic Algorithm (GA) offer distinct advantages for tackling complex optimization problems, particularly in large-scale systems with numerous control variables and expansive search spaces. Their stochastic nature and independence from gradients make them adept at avoiding local minima, ensuring robust exploration of solution landscapes. A key strength of GA lies in their ability to handle discrete decision variables directly, a capability not inherent in traditional optimization techniques. This approach is particularly advantageous in scenarios such as PNC design, where pipe diameters and thicknesses must be selected from a set of commercial sizes available in the market. Rounding-off solutions found by continuous variable-based techniques posed challenges and often resulted in infeasible solutions [1]. In contrast, GA seamlessly integrate this discrete nature into the optimization process, eliminating the need for cumbersome rounding procedures and ensuring feasibility without compromising the quality of the solution. GA alleviates this issue by inherently considering discrete variable constraints, ensuring that solutions remain feasible while maximizing optimization efforts [172]. Initially introduced by Goldberg [73, 72], GAs have been widely applied to pipeline optimization problems, as demonstrated by various researchers [53, 60, 155, 27, 35, 99, 161, 1, 172, 185, 110, 124, 68, 173, 156, 28]. GA simulate Darwinian selection logic [79, 37], with the following key steps:

1. Initial Population: Generate an initial population with random variability in parameter characteristics.
2. Evaluation: Assess each individual's fitness in the population using a predefined fitness function.
3. Survival: Selection of individuals based on their fitness values to advance into the next generation. The "survival of the fittest" principle is commonly applied. This step is crucial in guiding the evolution of the population towards fitter solutions.
4. Selection: Choose individuals to participate in mating based on predefined selection mechanisms. Different selection strategies can enhance algorithm convergence.
5. Crossover: Combine selected parents to produce offspring using crossover operators. The crossover operator requires problem-specific information, such as variable bounds.

6. Mutation: Introduce random changes to offspring with a predefined probability to enhance population diversity.
7. Iteration: Repeat the evaluation, selection, crossover, and mutation steps iteratively until a termination condition is met.

4.1.3.2 BPSO

Particle Swarm Optimization (PSO), introduced by Kennedy and Eberhart [101], is inspired by social behaviours observed in natural phenomena like the flocking of birds. PSO works by maintaining a population of particles, where each particle represents a potential solution to the optimization problem. The current population particles traverse the search space, adjusting their positions based on both their individual experiences (personal best) and the collective experiences of neighbouring particles (global best). Utilizing a swarm of particles, the algorithm employs velocities influenced by the best solutions found locally and globally. Social behaviour is integrated by incorporating globally or locally best-found solutions for velocity updates, while cognitive behaviour is determined by each particle's personal best solution. Achieving a balance between cognitive and social components ensures the algorithm's efficacy across various optimization problem statements. While the classical PSO algorithm is well-suited for continuous optimization problems, it requires adaptations to handle binary optimization problems where the solutions are represented as binary strings. Boolean Particle Swarm Optimization (BPSO) is a specialized variant of PSO designed specifically for binary optimization problems [102]. In BPSO, each particle's position is encoded as a binary string, where each bit represents a decision variable that can be either 0 or 1. BPSO utilizes a binary representation to efficiently explore discrete solution spaces, making it ideal for problems like feature selection, combinatorial optimization, and pattern recognition. The algorithm comprises key components: (1) Particles: A population of candidate solutions, each represented by a binary string; (2) Fitness Function: Evaluates the quality of a solution, typically defined by the specific problem at hand.; (3) Velocity: Associated with each particle, influencing its movement in the search space. In BPSO, velocity determines the probability of a bit flipping in the binary string. The steps involved in the BPSO Algorithm are as follows:

1. Initialization: Create an initial population of particles with randomly generated binary strings and initialize their velocities.
2. Evaluate Fitness: Compute the fitness score for each particle using the designated fitness function.

3. Update Personal Best (pbest): Compare the current fitness of each particle with its historical best (pbest). If the current solution is better, update pbest.
4. Identify Global Best (gbest): Determine the particle with the best fitness score among all particles (gbest).
5. Update Velocity: Adjust the probability of each bit flipping in the binary string based on the particle's current velocity, pbest, and gbest.
6. Update Position: Adjust the position of each particle according to its current position and velocity.
7. Repeat: Iterate through steps 2 to 6 until a termination criterion is satisfied (e.g., maximum iterations or convergence/stagnation of the algorithm).

4.1.3.3 NSGA

The Non-Dominated Sorting Genetic Algorithm (NSGA), as outlined in [56], is specifically tailored for addressing multi-objective optimization dilemmas where objectives are at odds with one another; improving one may deteriorate another. Unlike traditional optimization algorithms that target a single optimum, NSGA aims to discover Pareto-optimal solutions that balance conflicting objectives. Through the iterative application of genetic operators like selection, crossover, and mutation, NSGA progressively refines a population of candidate solutions toward the Pareto-optimal front. Efficiently handling optimization challenges with multiple conflicting objectives, NSGA attempts to generate a set of non-dominated solutions wherein no single solution surpasses others across all objectives. It maintains population diversity through non-dominated sorting and crowding distance, thus ensuring a wide range of trade-offs. Elitism, a practice of retaining top individuals from each generation, safeguards the best solutions, ensuring they persist through the evolutionary process. Thus, NSGA efficiently navigates multi-objective optimization landscapes, yielding diverse, non-dominated solutions covering the problem's solution space effectively. The following steps explain the functioning of the NSGA algorithm:

1. Initialization: It involves creating an initial population of candidate solutions, either through random generation or employing stochastic techniques. Each solution in this population represents a potential solution encoded as a vector of decision variables.
2. Evaluation: Determine the fitness of each candidate solution by calculating its objective function values, taking into account multiple conflicting objectives simultaneously. Determine dominance relationships among individuals.

3. **Non-dominated Sorting:** Individuals are classified into different Pareto fronts based on their dominance relationships. Perform non-dominated sorting to categorize solutions, with the first front containing non-dominated solutions and subsequent fronts containing solutions dominated only by those in preceding fronts.
4. **Crowding Distance Assignment:** It encompasses the computation of the crowding distance for each solution within every Pareto front, assessing its distance to neighbouring solutions in the objective space. Solutions with larger crowding distances play a more significant role in preserving diversity.
5. **Selection:** The parent solutions for the next generation are selected based on both non-dominated sorting & crowding distance. Solutions from higher Pareto fronts and those with greater crowding distances are prioritized.
6. **Crossover & Mutation:** Apply crossover and mutation operators to generate offspring solutions from selected parents. While crossover combines information from parents, mutation introduces random alterations to promote further exploration of the search space.
7. **Replacement:** Form the next generation population by combining parent and offspring solutions. Use selection mechanisms like elitism or tournament selection to maintain a constant population size.
8. **Termination Criteria:** Mention the algorithm's stopping condition, such as reaching a maximum number of generations or achieving solution convergence.
9. **Result:** Generate a final population consisting of non-dominated solutions that represent trade-offs between conflicting objectives. Select the final solution based on assigned weights.

4.1.3.4 PNC Optimizer

The core objective of PNC design optimization is to determine the most optimal values for decision variables, aiming to either maximize or minimize the objective function while adhering to a set of constraints. The precision in selecting the optimal network configuration in the proposed work relies on an extensive database of recent feasibility reports and published information to ensure accuracy. However, the objective of this study is not to ascertain the exact cost of each component but rather to provide reasonable estimates for all essential components typically considered in practical TEC analyses of pipeline design. The choice of optimizer varies depending on the objective functions, such as Differential Evolution (DE), GA, Evolutionary Strategy (ES),

Stochastic Ranking Evolutionary Strategy (SRES), or Improved Stochastic Ranking Evolutionary Strategy (ISRES), for mono-objective or multi-to-mono objective functions. When aiming to optimize a pipeline network for both cost reduction and carbon emission minimization, employing a multi-objective optimization approach becomes essential. To address this, employing a multi-objective optimizer like ECM, BPSO, Boolean Manta-Ray Foraging Optimization (BMRFO), Univariate Marginal Distribution Algorithm (UMDA), or NSGA proves essential for effectively handling the multi-objective functions complexity. The proposed models are not intended to supplant or undermine the effectiveness of established manual methods; rather, they aim to illustrate that the complex and labour-intensive evaluation of multiple optimization processes can be expedited and the standardization of design procedures can be ensured through system-based assessment. Compared to the manual process, which typically consumes not less than 5 minutes for each configuration and 2 hours for further cost and emission analysis for each feasible solution by an average design engineer, the proposed framework executes within a fraction of a second on an 8GB RAM Core-i5 processor computer. Depending on the time horizon of the problem statement, two optimization methodologies are there: Single Horizon Optimization (SHO) Framework and Multi-Horizon Optimization (MHO) Framework. This work considers the GA, BPSO, and NSGA optimizers for mono-objective and multi-objective functions [37, 55]. The primary aim is to present a comprehensive framework for PNC design optimization, rather than comparing the performance of different optimizers. Additionally, this study does not focus on comparing various simulation methods or evaluating their processing and convergence. The impact of alternative optimizers on the results will be analysed in future research.

4.1.4 Average Pipeline Diameter

An upfront comparative analysis of pumping station design alternatives can be conducted based on changes in the number & placement of pumping stations. However, such simplicity is not possible for decision variables related to pipeline diameter, particularly in the case of large networks. Hence, the concept of Pipeline Length-Weighted Diameter (PLWD) is introduced, indicating variations in pipeline diameters along the pipeline length as described in equation (4.2). It's important to clarify that the PLWD doesn't precisely reflect the diameter of any specific pipeline section. Instead, it represents the average diameter, serving as a valuable metric for evaluating the overall post-optimization changes in diameter across the extensive pipeline network.

$$PLWD = \frac{\sum_{k=1}^n D_k \times L_k}{L} \quad (4.2)$$

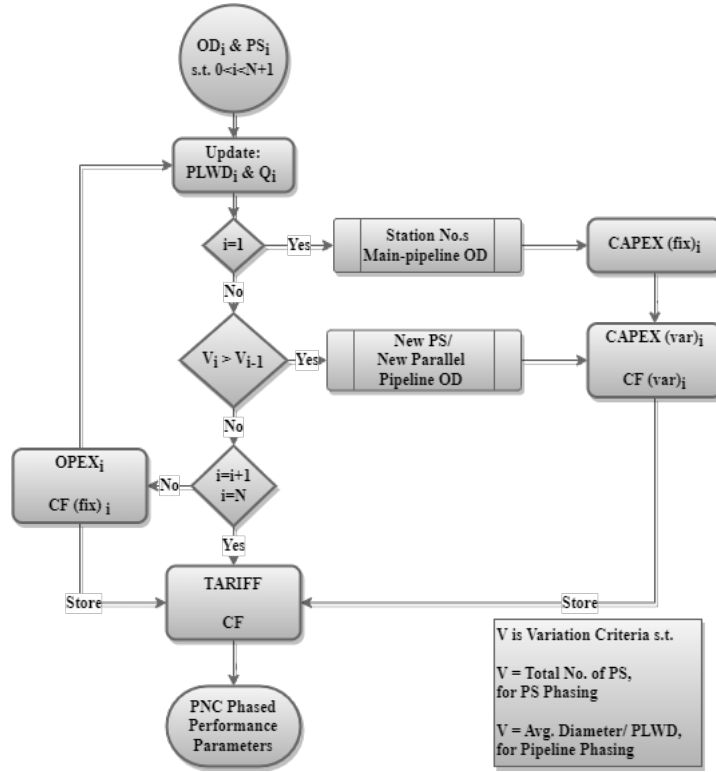


FIGURE 4.1: Multi Horizon Performance Parameters Analysis

4.1.5 MHO Performance-parameters Analyzer

Evaluating performance parameters within the MHO framework becomes more difficult as the PNC undergoes variations across different time horizons. Figure (4.1) provides a general schematic overview of this process, illustrating the assessment of multi-phase performance parameters for the specific problem statement and its corresponding optimization outcomes. The analysis involves phased network configurations across the time horizon conducted by the MHO analyser. Certain aspects related to pipeline construction remain consistent throughout the time horizon calculations and are accounted for in the initial year, including linefill cost, tank cost, and the initial phase PNC CAPEX along with its associated carbon emissions. Conversely, operation-related components such as OPEX & its associated carbon emissions vary and are computed for each distinct network configuration throughout the multi-horizon period. Any modifications in the PNC during the construction phases result in additional CAPEX and carbon emissions, necessitating updates in subsequent depreciation and pipeline OPEX. Moreover, the framework incorporates variable cost and environmental coefficients over the duration of the time horizon. Ultimately, a comprehensive evaluation of the overall cash-flow statement is undertaken based on phased CAPEX, OPEX, depreciation, and their associated components, ultimately leading to the determination of the pipeline's tariff.

4.2 Single Horizon Optimization Methodology

The optimization methodology aims to create a systematic programming algorithm that integrates the optimization components mentioned earlier according to the problem statement's requirements. This algorithm is designed to produce an optimal solution while considering technical, commercial, and environmental factors. The SHO is applied to the problem statement under the assumption of a consistent demand volume over the time horizon, thereby excluding considerations for capacity expansion or PNC extension design. The proposed nested optimizer framework handles interdependent binary and discrete decision variables while navigating through non-linear boundary conditions and penalty functions. The flowchart of the proposed SHO framework is depicted in Figure (4.2) and a brief description of the steps involved is provided below.

1. **Selection of Decision Variables:** The initialization phase involves gathering technical, environmental, and commercial inputs from the problem statement and creating sub-nodes.
 - (a) Technical parameters include the number of injection & receiving stations, product-wise source & demand volume, volume escalation, the material & grade of the line pipe and ambient temperature of each section.
 - (b) Geographical information encompasses receiving station chainage distance, elevation profile, the type of ROU route (new, existing, or parallel to other ROU such as roads, electrical lines, and railway tracks), and average design factor of each section.
 - (c) Economic parameters include the analysis period, tariff escalation, operational cost escalation, and desired Internal Rate of Return. As the proposed solution is developed using an open-source programmable tool, the default values of other parameters can be adjusted according to the pipeline designer's requirements.
2. Technical parameters encompass factors such as the count of receiving stations, chainage distance, product-specific demand volume, ambient temperature across sections, volume escalation, and the material & grade of line pipe. Commercial inputs include the analysis period, operational cost escalation, tariff escalation, and desired IRR. Environmental inputs encompass the carbon emission variation rate for steel and electricity. Additionally, product density and viscosity are updated based on the ambient temperature of the pipeline and the product type. Subsequently, a developed sub-algorithm generates an intermediate-node station based on the inter-station distances input/norms and terrain information such as pipeline elevation.

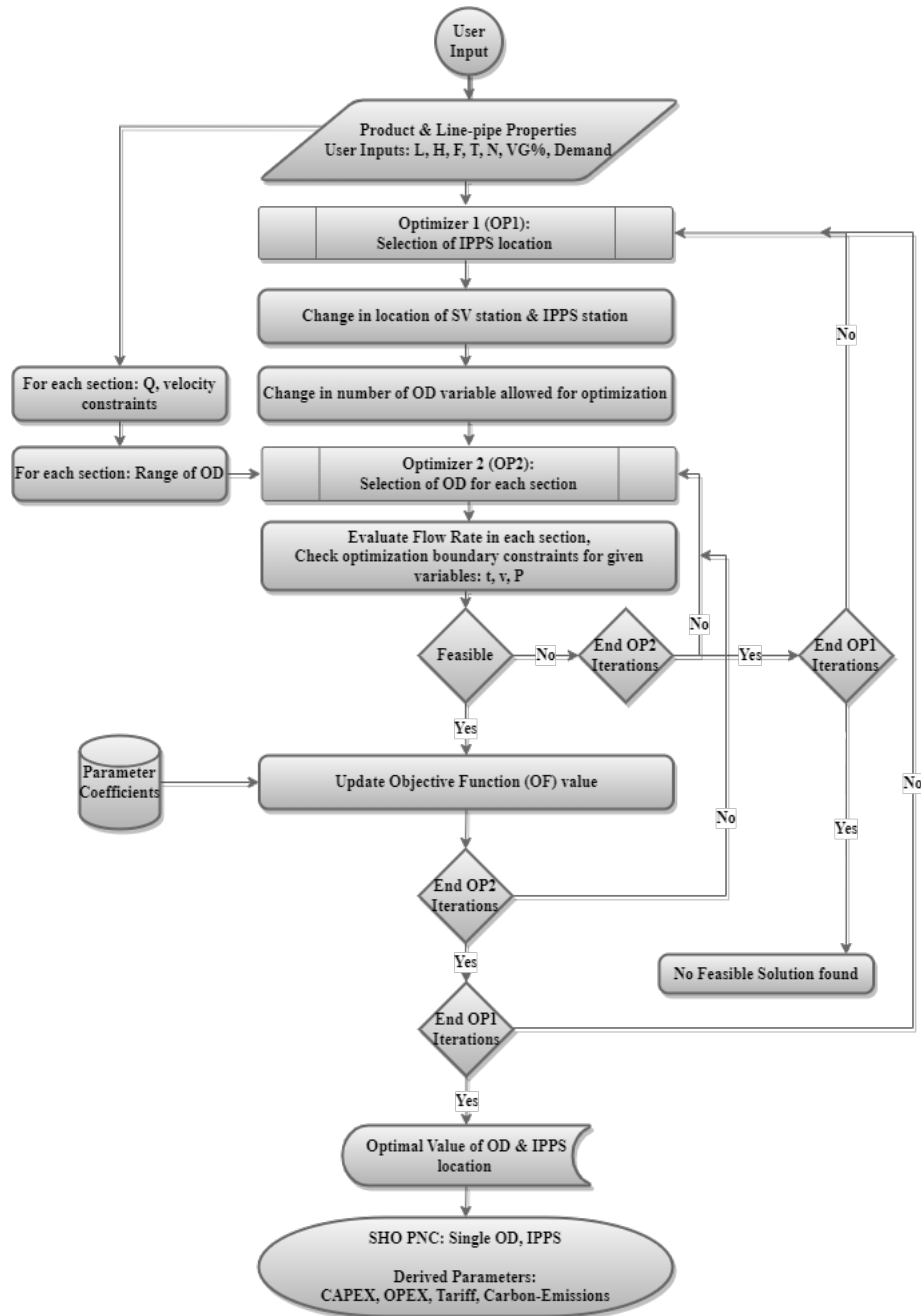


FIGURE 4.2: Single Horizon Optimization Methodology

3. **PNC Assignment:** This step involves the selection of optimizers and the steps involved in each optimizer for assigning decision variables—pipeline diameter, and number of pumping stations, & their locations.
4. **Optimizer Selection:** The choice of optimizer depends on the type of decision-making required. For the outer optimizer (Optimizer 1 for number of intermediate pumping stations & their locations (OP1)), which handles binary decision-making tasks such as determining the placement of intermediate pumping stations, Boolean optimizers like BPSO, BMRFO, or GA are suitable. The nested optimizer, denoted as Optimizer 2 for pipeline diameter (OP2), proceeds to choose the suitable range of pipeline diameters for each section from all commercially available options, guided by velocity boundary conditions. For simpler objective functions like mono-objective or multi-to-mono-objective, basic optimizers like GA, PSO, ACO, and SA can be used. However, for more complex objective functions involving multiple conflicting performance parameters, multi-objective optimizers like NSGA, or Mutli-objective PSO are better suited.
5. **Selection of Intermediate Pumping Stations:** The algorithm initiates by determining an initial set of intermediate pumping stations distributed across the nodes of the pipeline network. Within this outer loop, the first optimizer (OP1) assigns an initial population of intermediate pumping stations to the nodes. With these pumping station locations identified, the positions of SV and IPS are decided. Notably, the second decision variable for pipeline diameters remains fixed in sections succeeding SV nodes. This intricate interrelation relationship between decision variables necessitates the utilization of nested optimization. Subsequently, the nested secondary optimizer (OP2) specifies the range of pipeline diameters for each section from all available commercial diameters based on the velocity boundary conditions, as defined within the objective function of OP1.
6. **Pipeline Diameter Selection:** After the determination of potential sections for changing pipeline diameter based on SV nodes, the sectional flow rate is calculated according to the demand values outlined in the problem statement. The nested optimizer then determines the suitable range of pipeline diameters for each section from the available commercial diameters, taking velocity boundary conditions into account. This nested optimizer (OP2) ensures that the selected pipeline diameters meet the specified velocity constraints for each section. This boundary condition helps eliminate unwanted diameter options before the nested optimizer begins the solution search. The OP2 uses a common objective function shared by both optimizers to ensure coherent optimization.
7. **Optimization:** The optimization process consists of two main modules: Hydraulic Feasibility Evaluation and Nested Objective Function Analysis.

- (a) **Hydraulic Feasibility Evaluation:** This module assesses the hydraulic feasibility of the PNC diameters and pumping stations. It calculates the necessary flow rate for each section based on the final demand volumes. It ensures compliance with regulatory and standard specifications, including constraints on thickness, velocity, and pressure as outlined in equations (3.4), (3.8), and (3.12). These constraints must be adhered to without any violations. If any of the constraints are violated, the algorithm will skip the execution of the objective function module. Instead, it will revert to the optimizer for an alternative configuration. The algorithm ensures strict enforcement of boundary condition compliance. Moreover, this approach efficiently reduces program space and time complexity by avoiding unnecessary processing.
- (b) **Nested Objective Function Analysis:** Upon identifying hydraulically feasible solutions, the optimizer advances to the second module, where it computes the value of the objective function(s) using optimization techniques. The OP2 evaluates the value of performance parameter(s) and assigns them to the corresponding objective function. This may include pipeline tariff (which implicitly includes CAPEX, OPEX, volume, minimum IRR, and escalations), total emissions (from pipeline construction and operations), and combinations of these metrics. The user sets the convergence criteria to determine when the optimization algorithm should terminate. The optimization process within OP2 for various sets of decision variables persists until the convergence criteria are satisfied. This criterion can be defined as achieving a consistent solution across a predefined number of generations or reaching the maximum loop iterations. Following the convergence or termination of the inner optimizer (OP2), the outer optimizer (OP1) receives the objective function value and proceeds with its loop to explore further optimized values by examining different sets of intermediate pumping station locations. In this methodology, both optimizers utilize the same objective function within a nested architecture, ensuring the interdependence of both variables. Consequently, OP1 continues its search for further optimized values with different sets of intermediate pumping station locations, while OP2 is re-initiated. During the execution of the nested loops, the performance parameters, other than those used in objective functions, evaluated by the inner optimizer (OP2) may be overwritten by new PNC outcomes. To prevent this, an exclusive best value function is called at the end of the first loop to extract and preserve these values. This ensures that all critical performance parameters are retained for analysis and final decision-making.

8. **Optimization Results:** After the conclusion of the outer optimization analysis, the performance parameters corresponding to the best objective functions are obtained for the

optimal PNC decision variables. The outcomes of the optimization encompass financial and environmental parameters, including investment value and operating costs over the analysis period. This information facilitates informed decision-making and the efficient allocation of resources. Additionally, the minimum tariff required by the owner to operate the pipeline is calculated, ensuring profitability and sustainability. Furthermore, the estimation of the carbon footprint generated by the project investment and its operation enables proactive measures to mitigate the environmental impact of the pipeline network. The proposed PNC optimization framework provides a complete solution for the design & operation of the pipeline network, achieving the following outcomes:

- (a) **Accurate Sub-node Location:** Precisely determines the locations of sub-nodes, including SV and IPS, ensuring efficient network connectivity and optimal performance.
- (b) **Optimal Pumping Station Placement:** Determines the optimal locations & required number of intermediate pumping stations, with or without tap-off stations, to ensure consistent flow and pressure across the entire pipeline.
- (c) **Optimal Pipeline Dimensions:** Determines the optimal internal diameter for each pipeline section from the sets of commercial diameters & thicknesses, ensuring hydraulic feasibility and minimizing the risk of leaks and ruptures.
- (d) **Flow Rate & Pressure Calculation:** Calculates the flow rate, suction pressure, & discharge pressure at each node, facilitating real-time network monitoring and control for modelled PNC. This is crucial for future studies focused on optimizing pipeline operations.
- (e) **Tankage Requirement Determination:** Determines the tankage requirement at receiving stations for intermix mitigation and to manage demand volume uncertainty, ensuring an uninterrupted supply to customers.
- (f) **Cost Estimation:** Estimates the investment value and operating costs over the analysis period, enabling informed decision-making and efficient resource utilization. The absolute values of performance parameters may vary depending on the problem statement, user inputs, and prevailing conditions.
- (g) **Minimum Tariff Calculation:** Determines the minimum tariff necessary for the pipeline owner to ensure profitable and sustainable operation.
- (h) **Carbon Footprint Assessment:** Determines the carbon footprint resulting from the project investment, encompassing both construction and operation phases, enabling proactive measures to reduce the environmental impact of the pipeline network.

The primary aim of this study is to present a comprehensive methodology for optimizing the design of PNC, which can serve as a foundational framework for future research. It establishes standardized procedures and guidelines for the design and optimization of PNCs. The proposed research methodology provides a comprehensive and versatile framework for optimizing pipeline network designs, applicable across various domains such as natural gas, crude oil, refined products, LPG, water supply, and irrigation networks. While hydraulic and cost components may differ based on the specific application, the procedural steps outlined in the proposed methodology remain consistent. By following these steps, researchers and practitioners can develop PNCs that are efficient, cost-effective, and tailored to meet the unique requirements of their respective applications.

In summary, the proposed optimization methodology provides an efficient and effective approach to designing pipeline systems while considering technical, commercial, and environmental parameters. The use of nested optimizers and constraints ensures that the solutions are both feasible and optimal. Furthermore, the algorithm is adaptable to various types of objective functions and can be applied to different pipeline systems with minimal modifications.

The fluctuation in market demand volumes connected to the pipeline network is integral and essential for PNC design. Thus, relying solely on the outcome of SHO, which accounts for the final demand volume across nodes, may not yield an optimal PNC across the time horizon. Therefore, a novel methodology is introduced in the following section, focusing on multi-horizon optimization to strategically phase the PNC in response to variations in demand volume.

4.3 Multi-horizon Optimization Methodology

Forecasting long-term capacity requirements for a single customer is challenging, and the complexity increases exponentially when dealing with multiple customers. Pipeline systems must not only meet immediate capacity demands but also be designed for timely and efficient expansion to ultimate capacities. Regulators prioritize minimizing pipeline infrastructure and operating costs while ensuring the overall system efficiency. For pipeline owners, phasing the pipeline project mitigates the risk of substantial long-term capital investments by spreading the financial burden over time and aligning capacity increments with actual demand growth.

The pipeline represents a substantial & long-term investment requiring the ability to accommodate demand fluctuations across the multi-horizon period. Hence, consideration of a system-based Multi-Horizon Optimization (MHO) methodology for pipeline design enhances the pipeline owners' strategic decision-making regarding PNC expansion over the planning horizon. These

decisions may involve phasing pumping stations, installing sectional parallel pipelines, or a combination of both, all discussed in the systematic frameworks mentioned below. Moreover, the proposed multi-horizon variation of the PNC aims to minimize the initial investment cost, lower operational expenditure, and mitigate the risk of pipeline overdesign among various uncertainties, such as technological disruptions (e.g., the introduction of electronic vehicles) and government policies (e.g., development of Special Economic Zones, closure of industries). Additionally, it ensures optimal tariffs in line with network capacity utilization.

4.3.1 Pipeline Laying Phasing Methodology

Initially, there is a base flow rate, which may increase over several years (N years) due to a supply increase or the connection of new sources to the existing pipeline. In such scenarios, pipeline designers have three main options for addressing anticipated flow rate increases: (1) Oversized Design: This option involves initially installing a pipeline larger than necessary, which operates at less than full capacity for N years at the initial flow rate but becomes fully utilized once the anticipated flow rate is reached.; (2) Parallel Design: This approach entails independently optimizing parallel pipelines constructed before and after the anticipated flow rate increases.; (3) Pump Ramification: This method is applicable for multiple pumping station PNCs, recommending the phased construction of pumping stations rather than constructing them all in the initial commissioning year. This study not only examines the economic impact but also considers the environmental impact of opting for a phased PNC construction over an oversized pipeline.

This section discusses the parallel design approach for the pipeline project by using the Pipeline Laying Phasing Methodology. There is an inherent trade-off between oversized and parallel design options. [180] provided a contour plot to illustrate the trade-off point for various combinations of initial flow rate (Q_1), final flow rate (Q), ratio (Q/Q_1), and pipeline length. Their findings indicate that oversized pipelines are more favourable for shorter pipeline lengths but become less viable as the flow rate ratio (Q/Q_1) increases. For newPNC projects, the expansion methodology presented in this study can identify sections where a parallel pipeline may be necessary due to hydraulic bottlenecks, ensuring optimization of the objective function under increased flow conditions.

In the Pipeline Laying Multi-Horizon Optimization (PLMHO) framework, an additional parallel/loop pipeline is installed alongside the previously constructed main pipeline section. This approach is specifically applied in sections where the main pipeline's capacity becomes insufficient to handle the increased flow rate and meet the demand volume of subsequent receiving

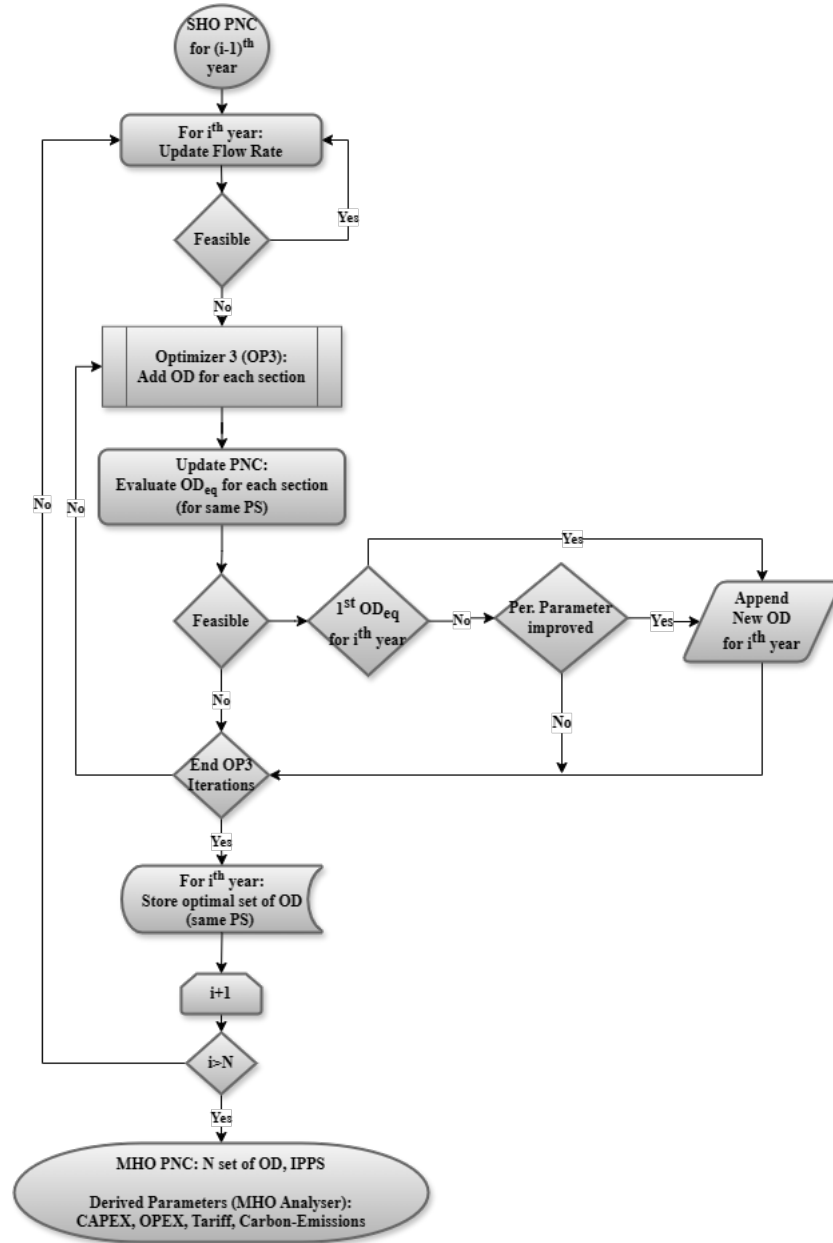


FIGURE 4.3: Pipeline Laying Multi Horizon Optimization Methodology

stations after the initial phase of PNC construction. Figure 4.3 illustrates the PLMHO technique, which is briefly described below:

1. **First Phase Optimization:** In the initial phase, the SHO optimizers (OP1 and OP2) determine the optimal PNC decision variables for the mainline pipe and pumping stations up to the p^{th} year based on user input and the estimated demand volume changes.

2. **Pipeline Laying Phasing Optimization:** For each subsequent phase, the PLMHO optimizer (Optimizer 3 for pipeline laying phasing (OP3)) assesses the technical feasibility for the updated demand volumes and augment the PNC if it becomes infeasible. OP3 identifies the appropriate diameters for additional loop pipelines across existing PNC sections to address pressure loss bottlenecks, without altering the number of pumping stations. The equivalent diameter for the i^{th} section is given in equation (4.3) [67]. To determine the optimal loop pipeline from multiple PNC options, OP3 uses the minimization of PLWD as an objective function and incorporates a penalty function for hydraulically infeasible solutions.

$$D_e = \left(\sum_{i=1}^n \left(\frac{f_{e_i}}{f_i} \right)^{2.5} \times D_i^{2.5} \right)^{0.4} \quad (4.3)$$

3. **PLMHO Result Analysis:** In the PLMHO context, significant changes primarily involve the loop pipelines and their associated systems. These include cathodic protection system and survey costs, laying expenses, ROU compensations, line-pipe costs, line fill costs, and updated operations & maintenance expenses. Additionally, key carbon emission variables are considered, accounting for extra steel production, varying carbon emission coefficients for the loop pipeline, transportation to the site, and ROU soil excavation and pipeline installation. The MHO analyzer performs a comprehensive cash flow assessment over the time horizon, incorporating elements such as CAPEX, OPEX, depreciation, and taxes. Based on this cash flow analysis, the tariff is determined. The MHO analyzer also calculates overall carbon emissions and evaluates the discount factored overall cost. This comprehensive analysis offers an all-encompassing perspective on the financial, environmental, and operational aspects of the pipeline project over its lifecycle. The effect of the designer's decision to select the initial phase year is also examined and discussed in a later section.

4.3.2 Pumping Station Phasing Methodology

In the Pumping Station Multi-Horizon Optimization (PSMHO) framework, the key strategy involves postponing the construction of intermediate pumping stations until a later year, provided that the PNC remains technically feasible even in their absence. This methodology assists pipeline owners in strategically determining the optimal timing for pumping station installation. This ensures that these stations become operational in line with the actual operational demands of the pipeline network, thereby mitigating investment risks associated with unforeseen

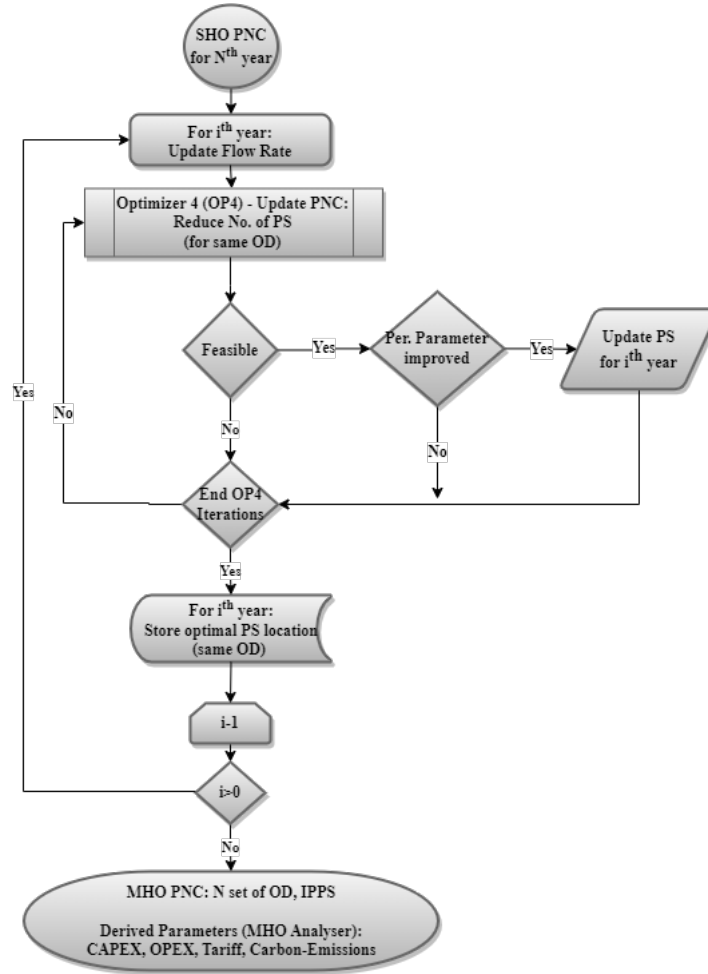


FIGURE 4.4: Pumping Station Multi Horizon Optimization Methodology

variations in initial demand forecasts. Consequently, this approach not only improves the financial aspects of the project but also contributes to environmental sustainability and operational efficiency. Figure (4.4) illustrates the PSMHO framework, briefly outlined as follows:

1. **Final-year SHO-based PNC:** The SHO optimizers (OP1 and OP2) will determine optimal decision variables for the final projected demand volumes of the problem statement.
2. **Pumping Station Phasing Optimization:** Following the execution of the SHO as mentioned in the previous step, the necessity of each intermediate pumping station is reassessed across different time horizons, in reverse order. This reassessment is conducted by a dedicated optimizer (Optimizer 4 for pump-station construction phasing (OP4)) without altering the pipeline diameters. In a given year, the number of pumping stations remains constant unless it is determined that their removal would still result in a technically feasible solution. In such instances, the construction of the pumping stations is deferred to

a later year. The objective function aims to minimize the number of pumping stations in a specific horizon while also ensuring its technical feasibility by penalty function. It's important to note that, unlike the previously discussed PLMHO, which involves substantial time lapses in the subsequently fixed pipeline laying stage, PSMHO offers flexibility, allowing for the phasing of pumping station construction for each year. This means that its subsequent phased investment can be adjusted anywhere from the near commissioning year to the farthest year in the time horizon.

3. **PSMHO Result Analysis:** In the analysis of PSMHO, variable CAPEX components arise from the additional process area required for new pumping station facilities, including mainline pumps, HVAC systems, basket filters, mass flow meters, sump tanks & their pumps, corrosion inhibition systems, fire-protection systems, and associated civil, mechanical, & instrumentation works costs for pumping stations. Anticipating challenges in land acquisition in future horizons, the cost of future pumping station land is considered in the initial phase. Similarly, significant carbon emission variables stem from constructing a new pumping station in place of an intermediate node and emissions from its operations, including mainline pumps. Subsequently, the MHO analyzer consolidates the impact of these variables and provides final performance parameter values.

4.3.3 Pipeline Laying & Pumping Station Phasing Methodology

In PLMHO, the loop pipeline is installed alongside the initial pipeline, and in PSMHO, non-pumping stations are converted to pumping stations across the PNC, to address additional hydraulic requirements and bottlenecks resulting from variations in demand volumes. Their optimizers exclusively alter a single optimal decision variable without changing the alternative decision variable initially derived from the SHO. To overcome this limitation and in search for further optimized results, a simple yet effective Pipeline Laying and Pumping Station Multi-Horizon Optimization (PLPSMHO) framework is proposed. It is illustrated in Figure (4.5) and described below:

1. **First Phase Optimization:** The SHO solution will assess the optimal PNC for the initial phase period using its optimizers (OP1 and OP2).
2. **Forward Horizon Optimization:** Consequently, augmentation to the initial phase PNC will be evaluated for pipeline laying using the PLMHO optimizer (OP3) for the following phases volumes $((p + 1)^{th}$ year). **Reverse Horizon Optimization:** For the set of PNCs derived from PLMHO across the given phase horizons, PSMHO is applied in reverse

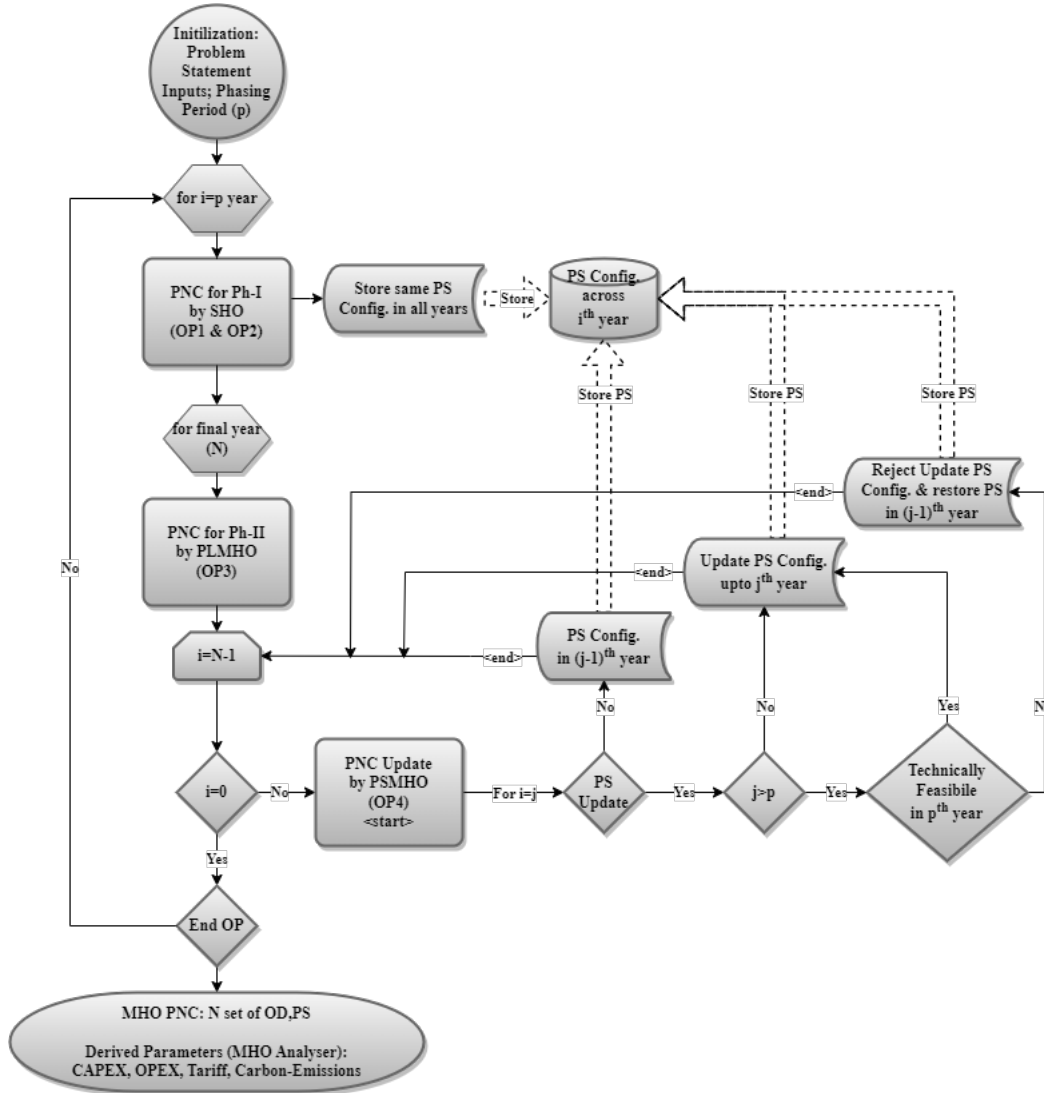


FIGURE 4.5: Pipeline Laying & Pumping Station Multi Horizon Optimization Methodology

chronological order. PSMHO optimizer (OP4) evaluates the need for intermediate pumping stations in reverse order and subsequently defers the construction of such stations to future horizons. This strategy reduces the number of pumping stations in the initial years, contingent upon the specific phasing year (j^{th} year) determined by PSMHO, as outlined below:

- Condition 1 - Pumping Station (PS) not updated: The number of pumping station(s) remains unchanged in the $(j - 1)^{th}$ year.
- Condition 2 - PS updated and j^{th} year $< p^{th}$ year: Pumping station phasing is updated up to the j^{th} year with a reduced number of pumping station(s).
- Condition 3 - PS updated and j^{th} year $\geq p^{th}$ year:

- i. For the updated PS, PNC is technically feasible for p^{th} year also: The PSMHO phasing result is admissible with a reduced number of pumping stations updated up to the j^{th} year.
- ii. For the updated PS, PNC is technically infeasible for p^{th} year also: The PSMHO outcomes for the all PNC pumping stations phasing are rejected upto j^{th} year. Consequently, the number & location of the pumping station(s) are reverted to their original values from the $(j - 1)^{th}$ year.

Pipeline Laying & Pumping Station MHO (PLPSMHO) Result Analysis: PLPSMHO

yields highly dynamic commercial and environmental parameters, ensuring the most optimal PNC design outcome. The performance parameters for the final set of the PNC across the multi-horizon period are evaluated by the MHO analyzer.

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Background

The results and discussion section provides a comprehensive analysis of the PNC design optimization outcomes. The first research objective was to design a Techno-Commercial Modelling of Pipeline Network. The detailed pipeline modelling is comprehensively discussed in Chapter 2 of this report. This analysis encompasses various elements, including pipeline thickness, product velocity, pressure at individual nodes, dynamic pump efficiency factor, tankage requirements, and associated components like flow rate, Reynolds number, & friction factor, among others. With advancements in simulation modelling using programming languages, PNC computations can now be performed dynamically, allowing for rapid and accurate evaluation of changes in product flow characteristics such as pressure, diameter, temperature, viscosity, density, elevation, and other variables [96]. To validate the accuracy of the proposed model, hydraulic outcomes were compared with those from existing literature on the China Multi-product Pipeline (CMPL) problem statement [186] and the Pipeline Studio software [163]. The results of this comparison are discussed in this section. Additionally, this research extends its objectives by investigating the impact of input variables on performance parameters, addressing a gap in the existing literature. The CMPL problem statement served as a reference for this analysis.

The second research objective aimed to determine the optimal pipeline section diameters and the location & number of pumping stations. As outlined in Chapter 3, a decision variable selection methodology was developed to accomplish this goal. This framework employs a two-tiered optimization process: the outer loop employs BPSO to optimize the locations & number of pumping stations, while the inner loop formulates the optimization based on specific pumping

station configurations using an optimizer (GA or NSGA) depending upon the type of objective function.

The third objective aimed to optimize the tariff structure for pipeline transportation, considering both capital and operating costs. This endeavour necessitates the meticulous modelling of capital and operating costs, as well as the derivation of tariff performance parameters, as elaborated in Chapter 2. Subsequently, through the selection of optimal decision variables for the tariff-based objective function, the pipeline transportation tariff was optimized. Additionally, extending beyond the primary research objectives, this study also addresses the impact of CE on PNC design optimization. This study explores the development of a multi-objective function, referred to as Tariff & Carbon-emissions (TCMOF), which combines tariff optimization with carbon emissions, aiming for a balanced commercial-environmental outcome in pipeline design. The single-horizon optimization (SHO) framework is utilised to analyse the performance parameters under the influence of the mentioned objective functions.

In extension to further optimization of single horizon optimization and to avert investment risk arising from the inaccurate demand forecast, this study proposed a novel multi-horizon optimization (MHO) framework. This approach formulates a phased construction of the pipeline project, optimizing its design across multiple time horizons. The details of SHO and MHO frameworks are discussed in Chapter 3. This section further examines the efficacy of different objective functions and the performance of both single and multi-horizon optimization strategies. Within this context, this section examines the performance of various objective functions and the effectiveness of both single and multi-horizon optimization strategies. The optimization methodology, executed in Python 3.8, leverages its versatility and extensive libraries for simulation modelling. The GA optimizer is deployed for mono-objective and mono-to-multi-objective functions, such as CAPEX, OPEX, Tariff, and Carbon emissions. The NSGA optimizer is implemented for the optimization of multi-objective functions, such as Overall-cost & Carbon-emissions (Overall-cost & Carbon-emissions Multi-Objective Function (OCMOF)) and Tariff & Carbon-emissions (TCMOF). The empirical analysis of PNC design optimization encompasses two case studies: the CMPL for Single Horizon Optimization and the CIPL for Multi-Horizon Optimization. These case studies compare the proposed methodologies with their respective base PNC mentioned in the literature, offering empirical insights into their effectiveness and competencies.

5.1.1 Hydraulic Model Validation

The outcomes of the proposed hydraulic model are compared with those derived from the reference paper [186] and the Pipeline Studio software, employing the same conditions and decision variables mentioned in the reference problem statement. Specifically, the physical characteristics of the product, node locations, interconnections, segment lengths, elevations, and demands are all aligned with those specified in the reference paper's problem statement. The hydraulic computations conducted in this study encompass steady-state PNC and compressible HSD, which have a higher density among the given multiproduct. The receiving station's location, demand volume, PNC diameter, and thickness adhere to the specifications outlined in [186]. The hydraulic outcomes of the proposed model for the reference PNC are tabulated in Table 5.1.

TABLE 5.1: Proposed hydraulic model outcome

PS/ Node	Pipeline Section	P_s (kg/cm ²)	v (m/s)	Re	P_f (kg/cm ²)	P_D (kg/cm ²)
DS		4.08				42.11
IPRS1	1: DS-IPRS1	22.48	1.00	89852.64	19.63	76.99
RS1	2: IPRS1-RS1	35.97	1.26	91971.55	41.01	35.97
RS2	3: RS1-RS2	14.36	1.34	86265.64	21.61	14.36
IPRS2	4: RS2-IPRS2	3.88	1.11	71544.34	10.48	66.08
IPRS3	5: IPRS2-IPRS3	10.95	1.12	60718.19	55.18	46.29
IPRS4	6: IPRS3-IPRS4	7.55	1.02	55535.87	38.74	80.96
RS3	7: IPRS4-RS3	33.19	1.23	54047.88	47.77	33.24
RS4	8: RS3-RS4	3.23	1.00	44229.62	29.96	

To validate the hydraulic model's output data accuracy, industry-standard software tools were utilized by previous researchers [144, 96, 171]. Likewise, in this investigation, an equivalent model is developed in the PipelineStudio software for the same pipeline network configuration and input components, as illustrated in Figure 5.1.

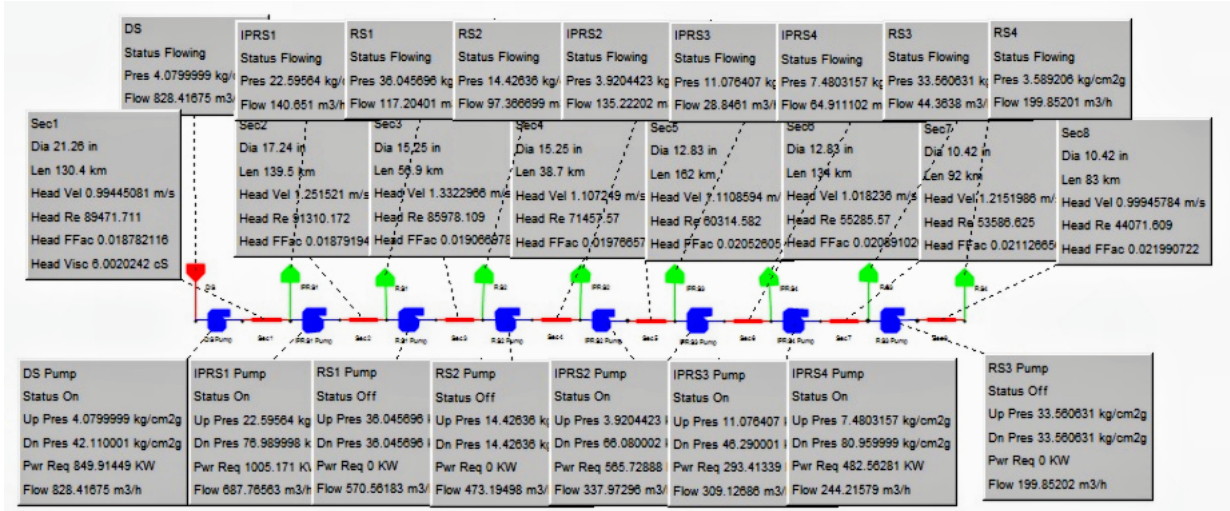


FIGURE 5.1: Pipeline Network Results in Pipeline Studio

To evaluate the accuracy and relevance of the proposed model, the hydraulic outcomes were compared with those reported in reference work [186] and the results obtained from the Pipeline Studio software. The findings, rounded to two decimal places, are detailed in Table 5.2.

TABLE 5.2: Comparative analysis of proposed model outcome with reference paper and Pipeline Studio

Station /Node	Section /Arc	Variation with Ref. PNC					Variation with Pipeline Studio				
		P_s	v	Re	P_f	P_D	P_s	v	Re	P_f	P_D
DS		0%				0%	0%				0%
IPRS1	1: DS-IPRS1	-1.1%	2.1%	0.6%	1.3%	0%	-0.5%	0.4%	0.4%	0.6%	0%
RS1	2: IPRS1-RS1	7.6%	1.5%	-4.3%	-7.8%	7.6%	-0.2%	0.7%	0.7%	0.2%	-0.2%
RS2	3: RS1-RS2	11.4%	4.5%	2.8%	5%	11.4%	0.7%	0.3%	0.3%	-0.8%	0.7%
IPRS2	4: RS2-IPRS2	-5.7%	10.6%	9.3%	16.4%	0%	-1.1%	0.1%	0.1%	1.3%	0%
IPRS3	5: IPRS2-IPRS3	-256%	8.4%	6.7%	12.4%	0%	-1.1%	0.6%	0.7%	0.3%	0%
IPRS4	6: IPRS3-IPRS4	5%	-0.2%	-1.1%	-1%	0%	1%	0.4%	0.5%	-0.2%	0%
RS3	7: IPRS4-RS3	3.7%	-0.5%	-2.2%	-2.7%	3.7%	-1.1%	0.9%	0.9%	0.8%	-0.96%
RS4	8: RS3-RS4	-5.6%	3.5%	1.4%	4.6%	0%	-11.1%	0.4%	0.4%	0%	

The discrepancies between the outcomes of the reference model and the proposed one may be ascribed to the limited details provided in [186], particularly concerning variables like pipeline roughness, known to influence hydraulic outcomes [144]. However, our model closely aligns with Pipeline Studio output, with minor differences except for the upstream pressure (P_s) at $RS4$, primarily due to the small absolute value of the variable. Notably, although there exists a significant deviation in the upstream pressure (P_s) of $IPRS3$ in our model compared to [186],

it aligns closely with the Pipeline Studio results. Hence, complete reliance on the output values provided in [186] may not be entirely reliable. Findings suggest that the proposed technical model yields results comparable to Pipeline Studio, with acceptable variations not exceeding 1.1% for the same PNC, except for the upstream pressure of the terminal RS and having an overall median of 0.3%.

5.1.2 Input Variables Sensitivity Analysis

To evaluate the performance parameters and conduct a sensitivity analysis on input variables, the case study of CMPL is considered as the base problem statement PNC. However, to reflect practical PNC modelling examination, the base model has been modified as mentioned below.

1. Boundary conditions for thickness and velocity as specified in equations (3.4) and (3.8) are incorporated during PNC model.
2. The pump discharge pressure is set at 95% of the design pressure to maximize the asset utilization and accommodate demand uncertainties.
3. A minor pressure loss in the total pressure loss is accounted for.
4. The interface volume and necessary tankage for mitigation are calculated, along with contingency sales considerations.
5. A comprehensive financial performance parameters are considered such as CAPEX components (ignored in the previous research work) such as RS tankage cost, line-fill cost, SV & IPS stations cost, station land purchase, fixed components, and other costs associated with process equipment. Similarly, OPEX components such as O&M of pipelines and stations, manpower, administration, land maintenance, and insurance costs are considered.
6. Accounted the cost factor associated with land use along the pipeline route.
7. The discount factor, CPI, operating cost, and tariff are considered with annual escalation rates of 3%, 2%, 2%, and 1%, respectively, over a 25-year planning horizon, with the pipeline project being commissioned after the first year.
8. Annual depreciation of the pipeline and station installations is calculated using the written-down value method and is reflected in the cash flow during tariff calculations. items Incorporating various additional components in the carbon emission performance parameter, such as ROU excavation & soil erosion, tankage construction, station fugitive emissions, and dynamic carbon-emission coefficient.

9. Implementing SV and IPS stations according to the practical design of thePNC in the base model increases the number of nodes from 9 to 21, enhancing pipeline safety and operation. The modified CMPL network includes 21 network nodes, 20 pipeline arcs, and 8 receiving stations, potentially serving as points for locating pumping stations during PNC design optimization. This graphical notation of the modified base CMPL PNC is illustrated in Figure 5.2.
10. While the base problem assumed a constant demand volume and flat terrain, this study considers a hypothetical value for these variables during sensitivity analysis to explore their impact on performance parameters.

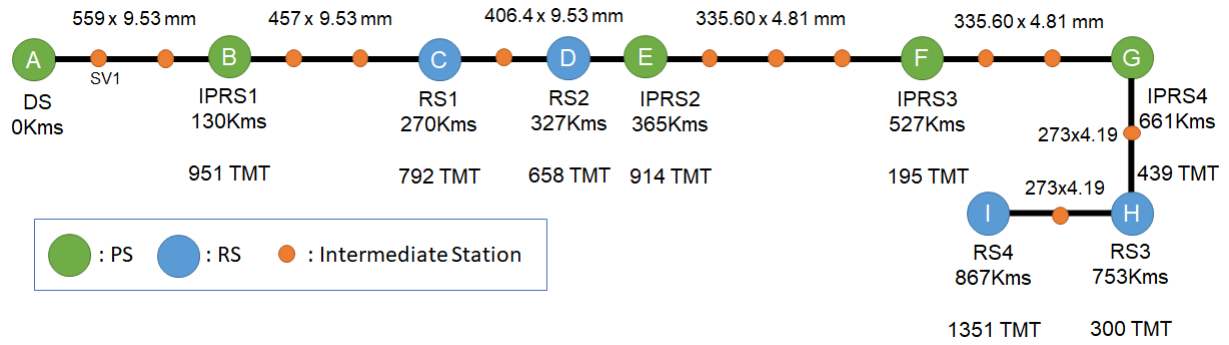


FIGURE 5.2: Modified CMPL PNC post intermediate stations.

The following subsections discuss the performance parameters of the modified reference model and present the results of sensitivity analyses based on various input variables.

5.1.2.1 Elevation Impact

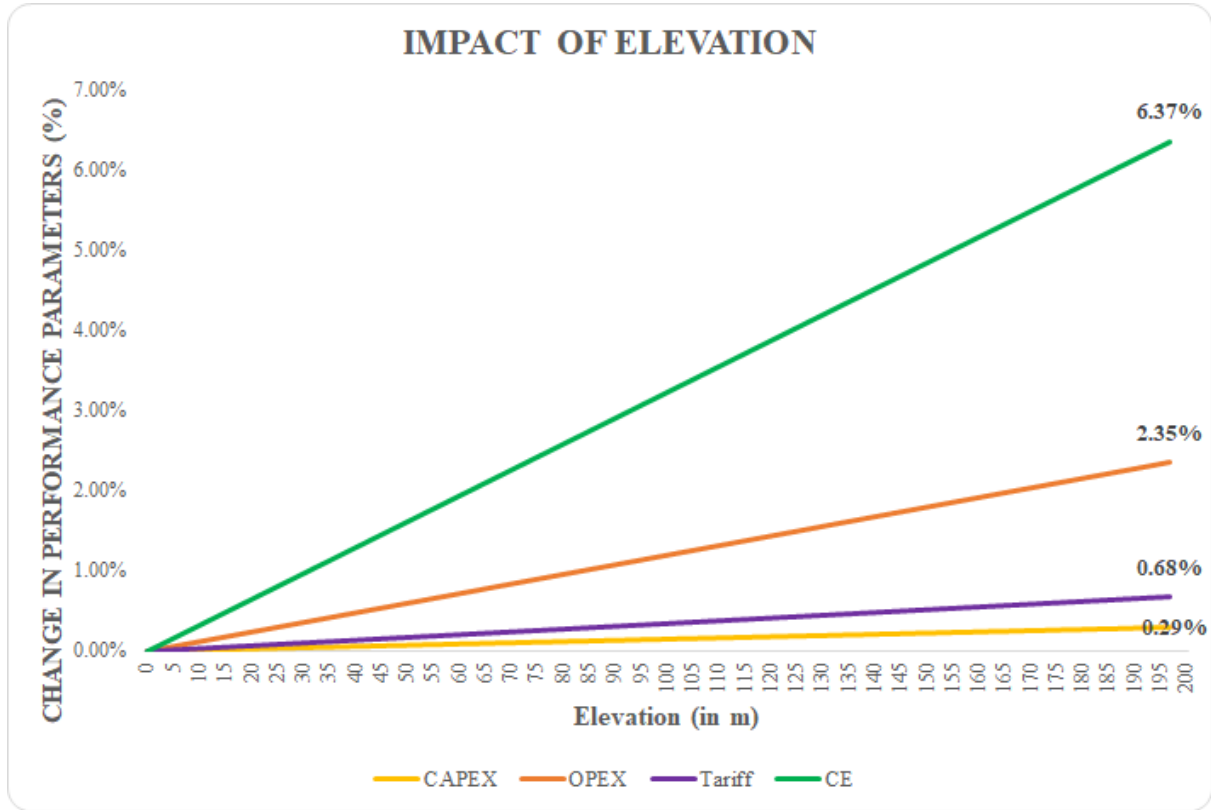


FIGURE 5.3: Impact of Elevation on Performance Parameters.

The elevation of the pipeline ROU plays a crucial role in the determination of the overall pressure profile, with the PNC's capacity to manage inaccurate elevation inputs relying heavily on available spare capacity. In the base case study PNC, the author have assumed a uniformly flat terrain. To investigate the elevation's impact on performance parameters, the elevation for sections between IPRS1-IPRS2 is hypothetically altered with a resolution of 1-meter variation. As depicted in Figure 5.3, performance parameters exhibit a linear increase with rising elevation until the PNC reaches its threshold to accommodate additional pressure loss resulting from elevation changes. However, beyond an elevation change of 197 meters, for the given problem statement, the outcomes become hydraulically unfeasible. On the other hand, a continuously descending slope of the ROU terrain potential energy change aids in overcoming the friction losses, leading to decreased pumping power requirements and consequently, lower values of performance parameters. While the influence of elevation on CAPEX and tariff remains minimal after the pipeline commissioning, it significantly influences other performance parameters such as OPEX and carbon emissions, with variations of up to 2.35% and 6.37%, respectively. It is

pertinent that neglected or incorrect elevation values during PNC modelling can result in infeasible solutions for the same demand volume and problem statement. Hence, it's crucial to consider pipeline ROU elevations meticulously during PNC modelling to ensure the system's feasibility.

5.1.2.2 Product Temperature Impact

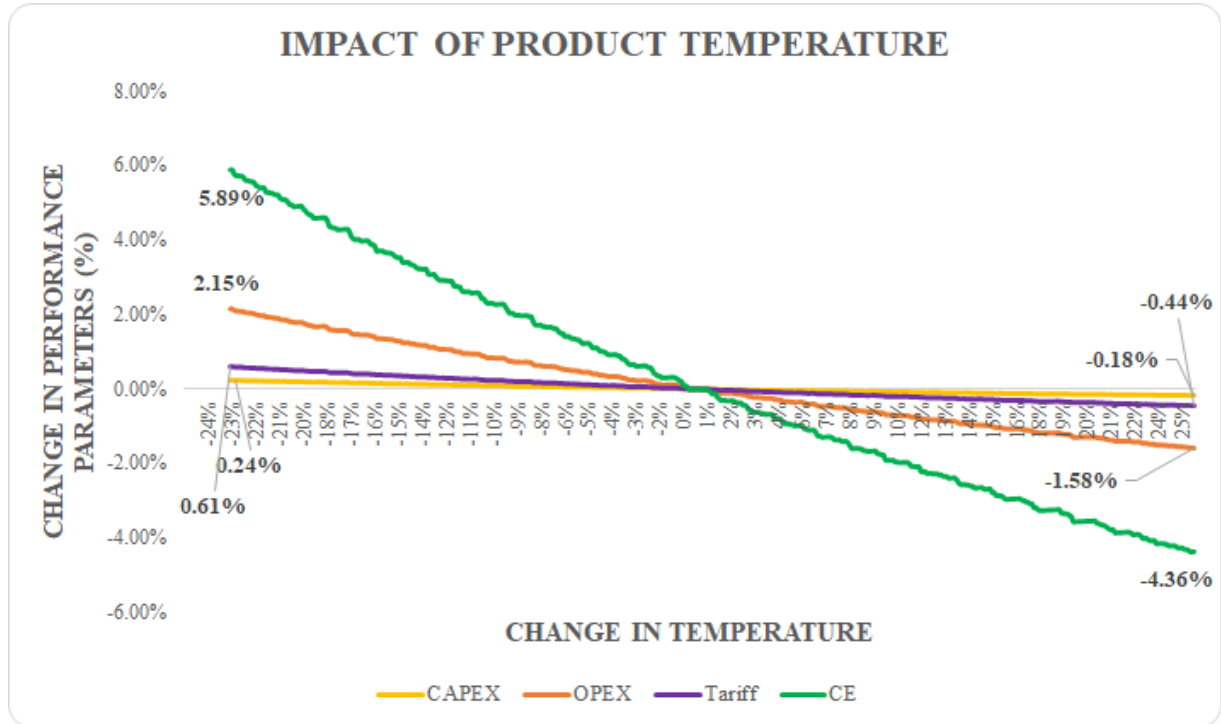


FIGURE 5.4: Impact of Product Temperature on Performance Parameters.

In liquid pipelines, product density and kinematic viscosity typically increase as temperature decreases, while the opposite trend occurs in gas pipelines. Illustrated in Figure 5.4, a temperature increment results in decreased frictional pressure loss within the pipeline, which intensely impacts the PNC hydraulic performance. Consequently, this leads to reduced energy consumption by pumps, thereby lowering both CAPEX and OPEX. Similar to the sensitivity observed in the elevation profile, temperature exerts a significant influence on carbon emissions but exhibits minimal impact on CAPEX. Failure to consider the appropriate temperature conditions of the transported fluid during design optimization may render the solution hydraulically unfeasible in the real-time scenario. The sensitivity analysis reveals that the reference problem statement solution becomes infeasible when the temperature decreases beyond 23% of the input product temperature. In the interest of streamlined pipeline design assessment, it's proven that

the lowest temperatures of the liquid product shall be considered rather than relying on average temperatures during thePNC design. Additionally, this study incorporates the influence of fluid temperature on product viscosity and density for each section, segmented by a maximum distance of 50 km, ensuring comprehensive hydraulic analysis.

5.1.2.3 Volume Change Rate Impact

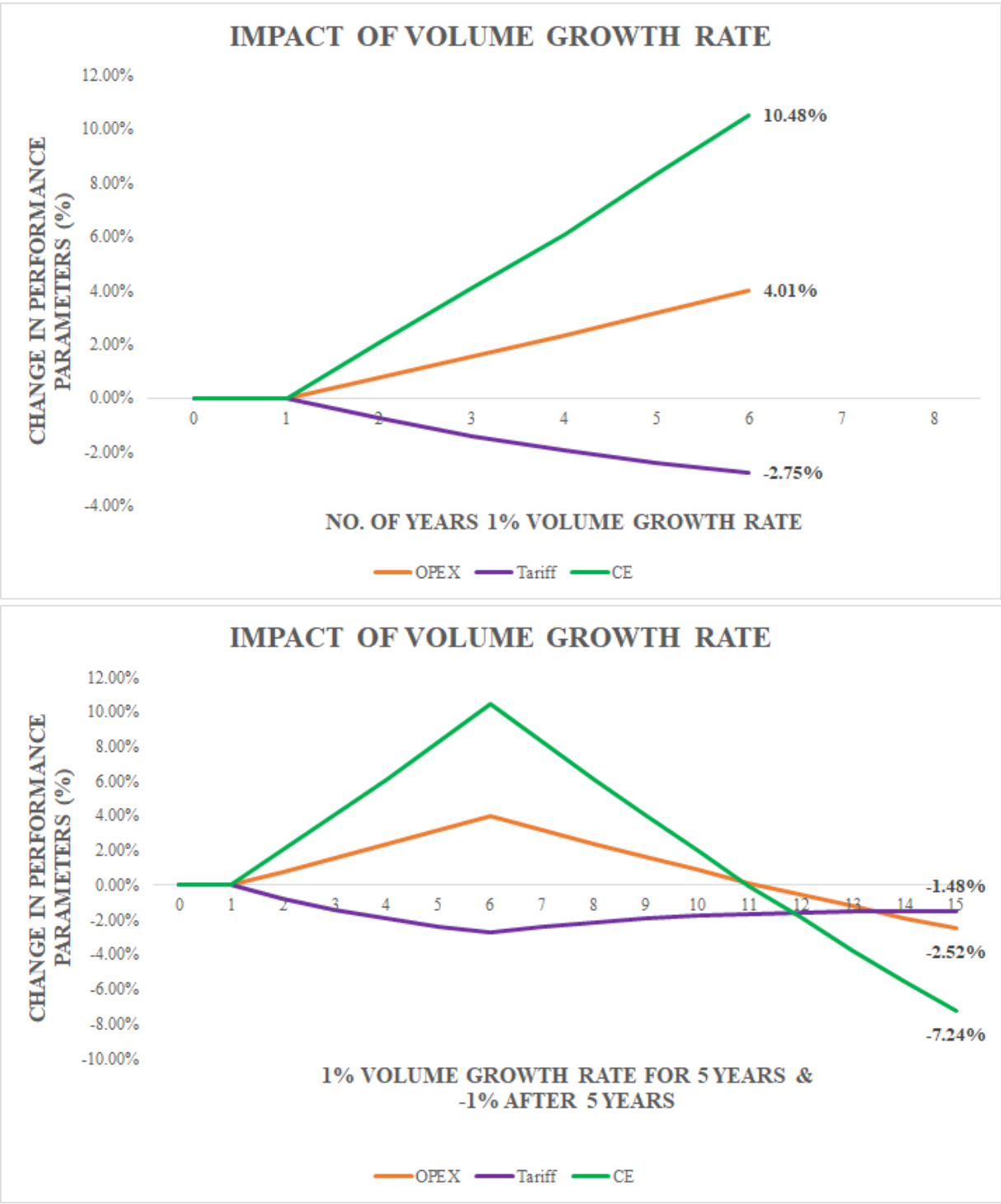


FIGURE 5.5: Impact of Volume Rate on Performance Parameters.

The cornerstone of PNC design lies in meeting the demand at the receiving station (RS), and assuming a constant demand volume over the entire time span is inaccurate. As depicted in The study by [186] assumed a constant demand volume, however, the outcome shows that the base case PNC could handle additional volumes for five years post-commissioning, given a growth rate of 1% per annum due to its spare capacity. Figure 5.5, an erroneous estimation of the volume growth rate can significantly impact performance parameters and even the technical feasibility of the PNC solution. It's worth noting that, unlike the overall cost performance parameter, an increase in demand volume results in a decrease in tariff value, despite potential rises in operational costs, owing to augmented revenue collection. Thus, the tariff functions as a performance parameter that not only guarantees desired returns for the owner but also provides a balanced approach to commercial analysis by addressing the concerns of owners, users, regulators, and end-customers alike. Therefore, utilizing the tariff-based objective function is recommended for a comprehensive techno-commercial analysis of pipeline projects.

The PNC network's ability to accommodate changes in demand volume comes at the expense of spare capacity, which may result in its over-design. Hence, it's crucial to balance between spare capacity with performance parameters, a research domain known as uncertainty analysis in PNC design and operations [166, 24, 148]. Accurately estimating demand volumes and growth rates is pivotal for long-term capital-intensive investments like pipelines. Incorrect designs for varying demand volumes can significantly impact the pipeline owners' balance sheets and stakeholders. To mitigate the risk of erroneous design, PNC expansion should be phased across the time horizon to mitigate uncertainties arising from multiple plausible future demands and errors in initial estimates. The subsequent sections will delve into examining the impact of PNC phasing during design optimization. The proposed model also designed simple mitigation measures to enhance PNC model robustness, such as additional tankage for contingency sales volume, and design margins in pump discharge pressure, & margins over theoretical calculations.

Furthermore, the study investigates the inverted v-shape curve of the volume growth rate, anticipated due to interruptions in oil and gas demand resulting from the availability of alternative energy sources and technologies, as illustrated in Figure 5.5. Diminishing oil and gas demand has a negligible impact on techno-commercial parameters, but phasing the pipeline project will help avert further risks of under-utilization of the pipeline capacity. OPEX and carbon emissions continue to decrease with decreasing demand volume, but the tariff remains almost constant, 1.48% lower than the base-model tariff due to higher cash flow in the initial years with a lower influence of the discount rate. Therefore, pipeline owners should aim for higher volume realization during the initial phase to maximize investment returns.

5.1.2.4 Tankage & Linefill Impact

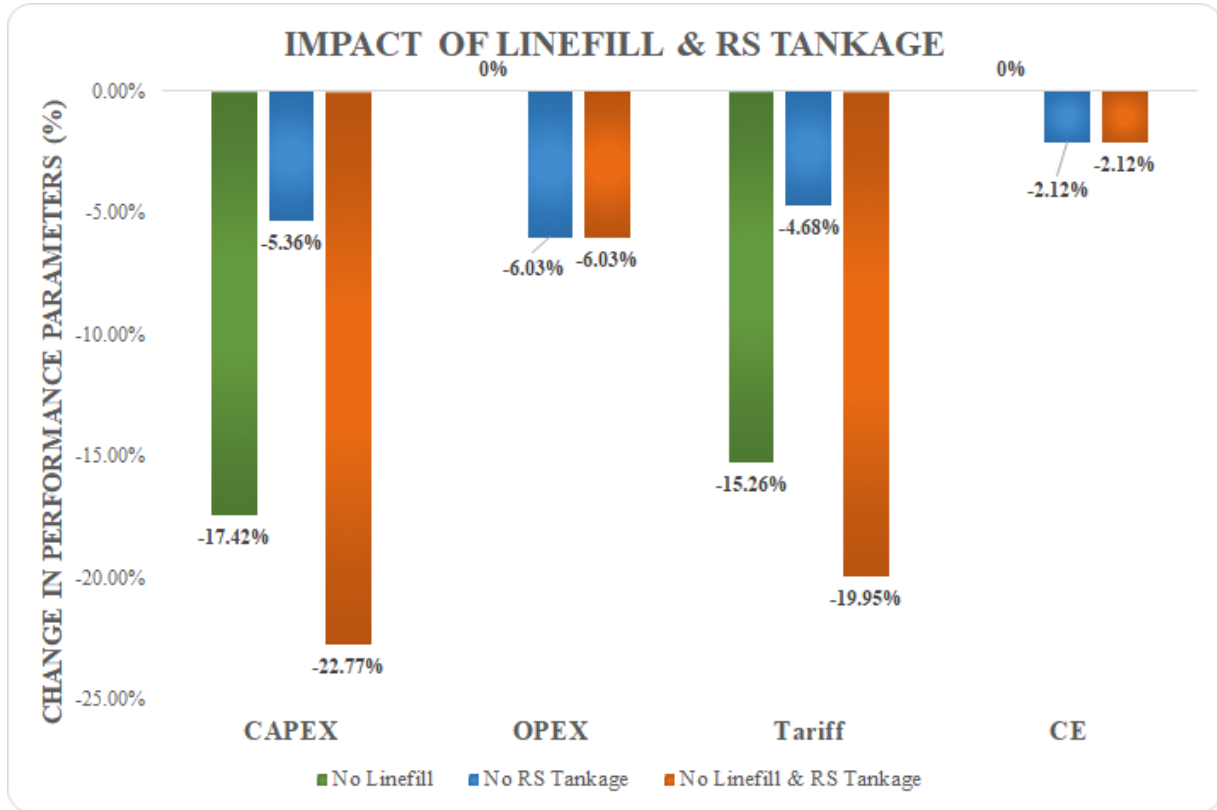


FIGURE 5.6: Impact of Tankage & Linefill on Performance Parameters.

The construction of storage tankage is one of the fundamental requirements in the pipeline project and it necessitates a substantially greater amount of steel than the models suggested in previous literature, impacting all performance parameters significantly. As depicted in Figure 5.6, in the CMPL case-study PNC, tankage construction contributes 17.42%, 6.03%, 4.68%, and 2.12% to CAPEX, OPEX, tariff, and carbon emissions, respectively. The pipeline acts as a potential storage unit since it is always filled with the product [100]. The expenses related to linefill & tankage are unavoidable and heavily influenced by the pipeline diameter. Ignoring these factors during the PNC design could lead to a solution preference for a larger pipeline diameter over-emphasizing the pumping stations. As illustrated in Figure 5.6, linefill constitutes 5.36% of the CAPEX in the CMPL solution. The costs of tankages & linefill have a significant impact on the commercial aspects of the pipeline project, with an overall effect of 22.77% on pipeline investment and 19.95% on tariff. Thus, it is essential to consider these variables during the modelling process.

5.1.2.5 SV/IPS installations, & Dynamic Carbon-emission Coefficients, Minor Losses Impact

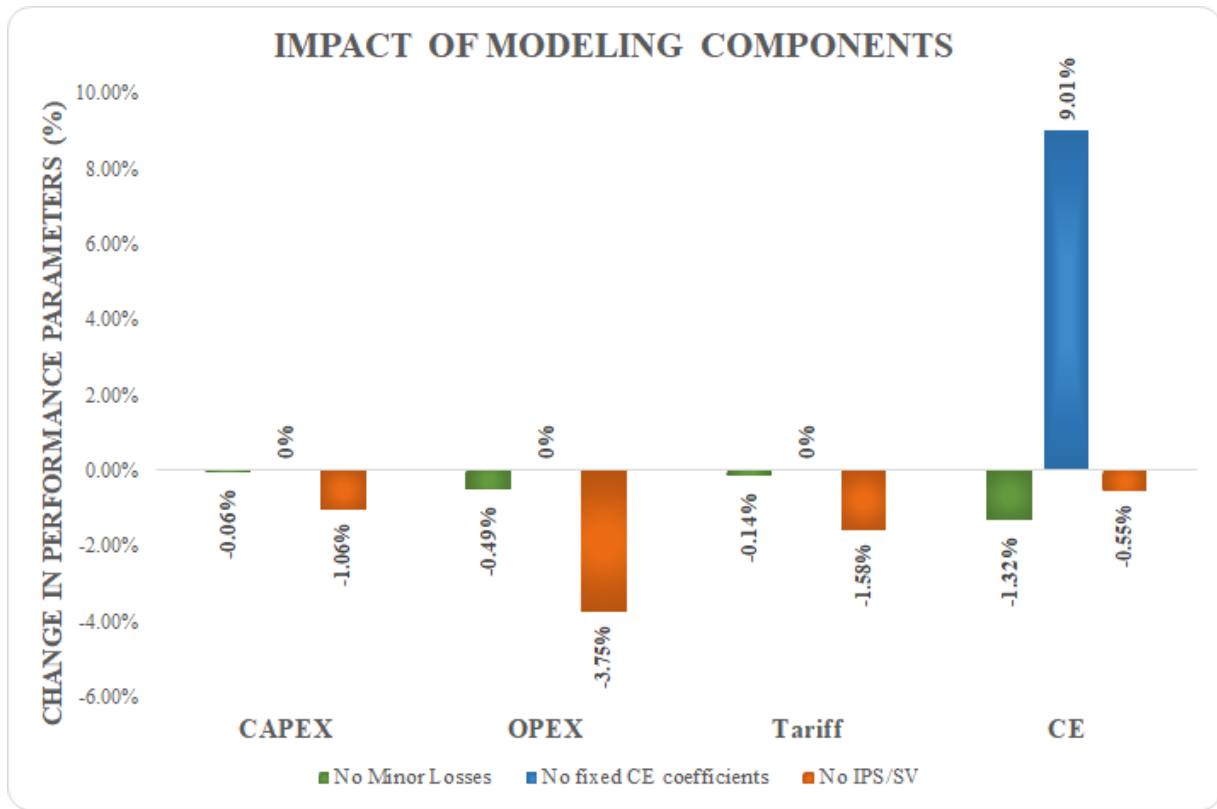


FIGURE 5.7: Impact of SV/IPS installations, & Dynamic Carbon-emission Coefficients, Minor Losses on Performance Parameters.

Figure 5.7 illustrates the impact of excluding minor losses, dynamic carbon-emissions components, and intermediate non-pumping stations on performance parameters. The construction of SV and IPS is essential for compliance with statutory requirements for safe pipeline operation and maintenance, though it does not affect the solution's feasibility. Figure 5.7 shows that construction of these stations increases CAPEX by 1.06% and OPEX by 3.75%, resulting in a marginal increase in the pipeline tariff. Carbon emissions also increase slightly by 0.55%. Moreover, incorporating these stations reduces the infinite potential points for intermediate pumping station construction to a finite number, thereby aiding the pipeline design engineer. Intermediate stations play a pivotal role in practical pipeline design, offering designers the opportunity to construct shared facilities for intermediate pumping stations. Co-constructing pumping stations with intermediate stations (RS, SV, IPS) not only optimizes costs but also contributes to reducing carbon emissions by several times, highlighting the importance of considering these stations in the overall design process [186].

The results indicate that while dynamic carbon emissions coefficients do not affect pipeline feasibility over time, they do increase overall carbon emissions by 9% for CMPL PNC analysis of 25 years. This increase is crucial for problem statements where carbon emissions are used as fitness functions during PNC optimization. Therefore, they form a major component of the pipeline's overall carbon emissions and are essential for accurate PNC modelling & design.

When minor losses are not considered, the pump's energy consumption decreases as the pump discharge pressure requirement is reduced, leading to a proportional decrease in OPEX and carbon emissions. However, the impact on commercial performance parameters is minimal, with variations less than $\pm 0.5\%$, and can be overlooked for long pipeline networks if sufficient margin in pump discharge pressure is included to ensure hydraulic feasibility.

5.1.2.6 OPEX & Tariff Change Rate Impact

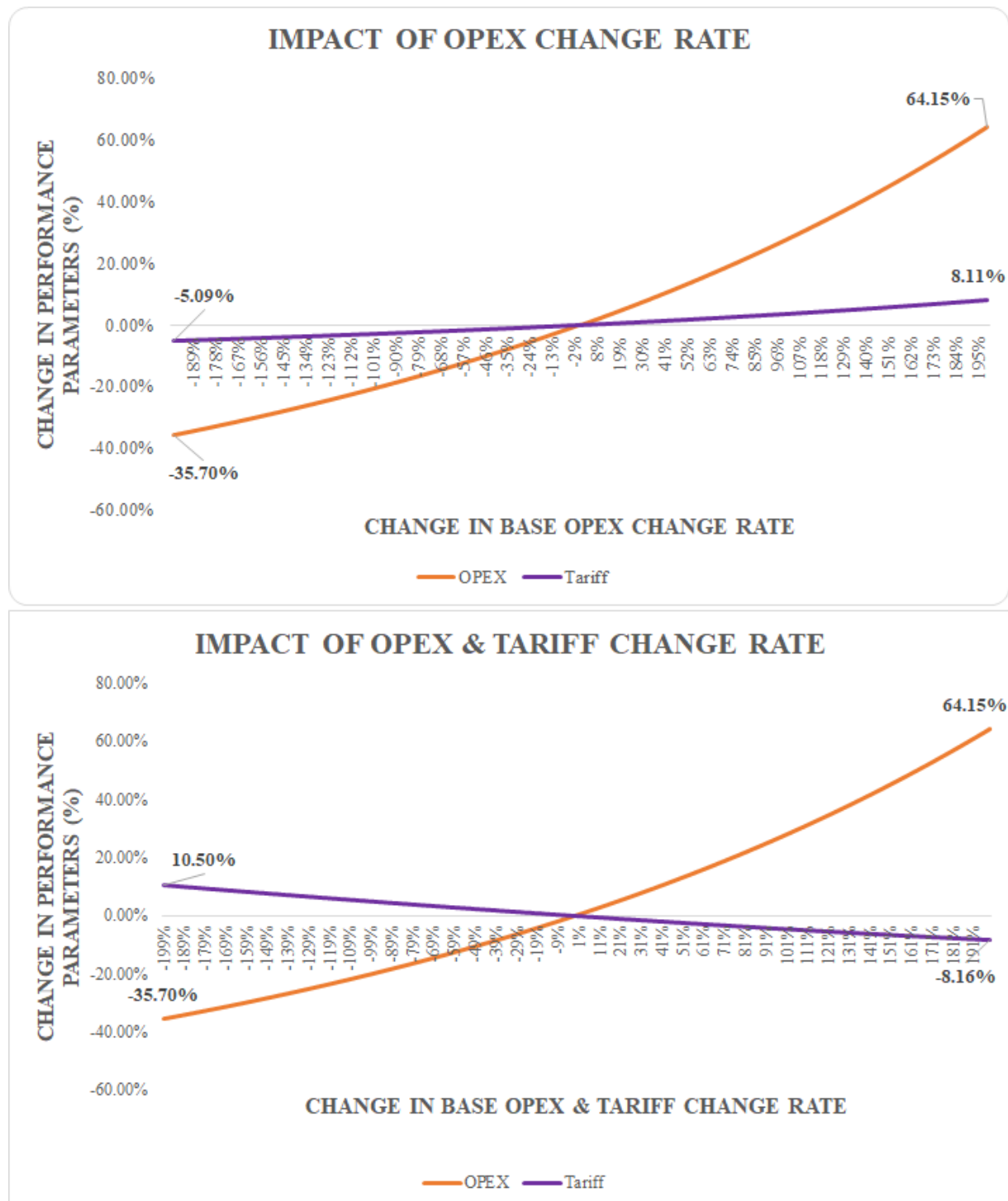


FIGURE 5.8: OPEX & Tariff Rate impact on Performance Parameters.

It is incorrect to overlook OPEX change rate, particularly concerning energy consumption and manpower costs, as this can ultimately lead to an inaccurate PNC end solution. As shown in Figure 5.8, an increase in the OPEX change rate causes a rapid rise in operating costs and vice-versa. In the modified case-study model, an OPEX change rate of 2% per annum is assumed. Increasing this rate to 4% per annum results in a 64.15% increase in overall operating costs, whereas reducing it to 0% per annum leads to a 35.70% decrease. Therefore, increasing the OPEX rate has a substantial impact on overall OPEX and incorrect OPEX escalation can bias the PNC outcome towards more pumping stations decisions rather than optimal pipeline diameter.

In the case-study model, a tariff change rate of 1% per annum is considered. The tariff value decreases significantly with an increase in the tariff change rate and vice versa. As shown in Figure 5.8, modifying the tariff change rate and OPEX change rate has opposite effects, but the former offsets the latter overall outcome. Thus, it is recommended that the regulators should closely scrutinize the tariff change rate factor when determining tariff values across the time horizon.

5.1.2.7 Phasing, Fixed Cost Components, Depreciation Impact

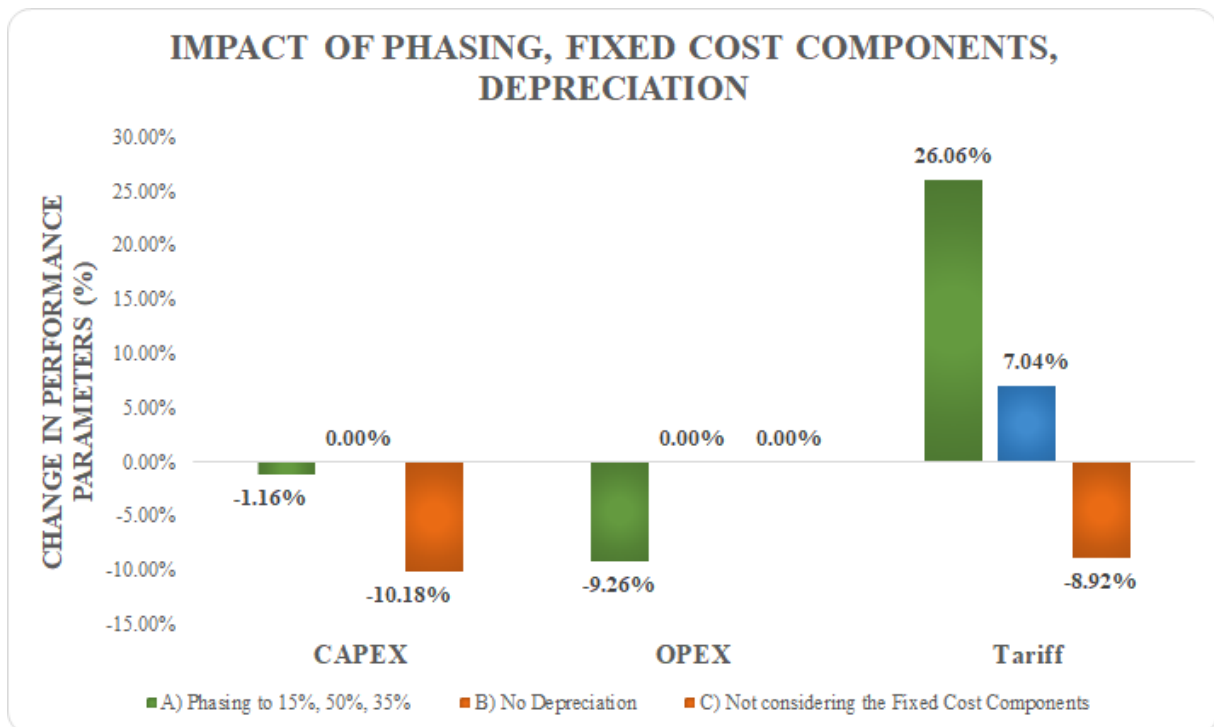


FIGURE 5.9: Phasing, Fixed Cost Components, Depreciation, Cost Escalation impact on Performance Parameters.

As previously mentioned, CAPEX phasing is essential for mitigating risks due to inaccurate demand volume estimates or uncertainties. In Case (A) in Figure 5.9, delaying pipeline commissioning results in a 26.06% increase in tariff because of postponed revenue generation. This is despite a slight 1.16% decrease in CAPEX due to the discount factor and a 9.26% decrease in OPEX due to prolonged non-operation. Notably, phasing the project doesn't mean delaying execution, which is not advisable. Instead, it involves designing and executing the PNC based on short-term demand, followed by gradual expansion or extension in phases as conditions are updated.

Depreciation significantly affects the cash-flow statement by reducing taxation cash outflow. As shown in Case (B), ignoring depreciation increases the tariff by 7.04%. Additionally, it's vital to consider CAPEX fixed components, which constitute at least 10% of the overall CAPEX for the CMPL. Hence, neglecting this important aspect can lead to inaccurate pipeline tariff calculations and a comprehensive techno-commercial analysis of the project must include all these factors.

The summary of the sensitivity analysis presented in Table 5.3 highlights the critical parameters affecting pipeline modelling. Key factors such as the elevation profile, temperature, and volume & its growth rate, significantly influence not only the commercial and environmental aspects but also the hydraulic stability of pipeline systems. While these parameters are essential in pipeline network design, it is noteworthy that only one-third of the existing literature incorporates them into pipeline modelling. On the other hand, while elements like pipeline linefill, the construction of RS tankages, and the implementation of SV or IPS do not directly affect hydraulic feasibility, they are integral to the pipeline's overall lifecycle and significantly impact cost and carbon emissions. Surprisingly, none of the previous works considered them in the pipeline TEC modelling. This research further investigates additional factors such as minor losses, dynamic carbon emissions, project phasing, depreciation of assets, fixed capital expenditure (CAPEX) components, operational expenditure (OPEX) escalation, and tariff escalation. These aspects are critical to understanding the techno-commercial performance of pipeline network design, and the study strongly recommends their inclusion in future pipeline TEC models. The summarised outcomes of the model parameters are as follows:

TABLE 5.3: Impact of parameters variation

Parameter	Literature Coverage	Impact	Essential
Elevation	35%	More discharge pressure, hence impact technical feasibility. Increase in OPEX & CE by 2.3% & 6.3% resp. (due to increased discharge pressure)	⇓
Temperature	17%	Impact density & viscosity hence impacts technical feasibility. Increased temperature of 25%, decreased OPEX & CE upto -1.5% & -4.3% resp.	⇓
Volume	35%	Increased flow rate, more frictional losses & hence, impacts technical feasibility. A 1%/year increase for 6 years, results in an increase in OPEX & CE by 4% & 10% resp. but tariff by -2.7%.	⇓
Linefill & RS Tankage	0%	Significant cost implications (22% CAPEX, 4% OPEX & 20% Tariff)	⇓
Minor Losses	5%	Slightly higher pumping pressure	
Dynamic CE	0%	Reduced fixed CE by 9% (in 25yrs)	✓
SV/IPS	0%	Impact decision variables & also commercial-environmental parameters	⇓
Project Phasing	0%	Decrease in OPEX but increased Tariff (late revenue realisation)	✓
Depreciation	0%	Impact tariff upto 9%	✓
Fixed CAPEX components	0%	10% & 9% part of CAPEX & tariff resp.	✓
OPEX Esc.	30%	Increase from 2% to 4% will increase overall cost by 64%	✓
Tariff Esc.	0%	Tariff escalation will increase the revenue, hence decreasing tariff value.	✓

5.1.3 SHO Outcome: China Multiproduct Pipeline

The effectiveness of the proposed SHO methodology is evaluated using the CMPL problem statement. After considering the velocity boundary condition, each of the 20 pipeline sections allows for a range of 6 diameters (ranging from 12" to 22"). Consequently, with 20 locations/nodes, the problem involves 140 decision variables, resulting in a staggering 767 hundred trillion possible

combinations. The effectiveness of the proposed SHO framework is evaluated using the CMPL problem statement, which poses a significant computational challenge due to its complexity. Further, the effect of different objective functions on the SHO results is examined, and these findings are depicted in Figure 5.10 to facilitate a comprehensive comparative analysis, which is extensively discussed below.

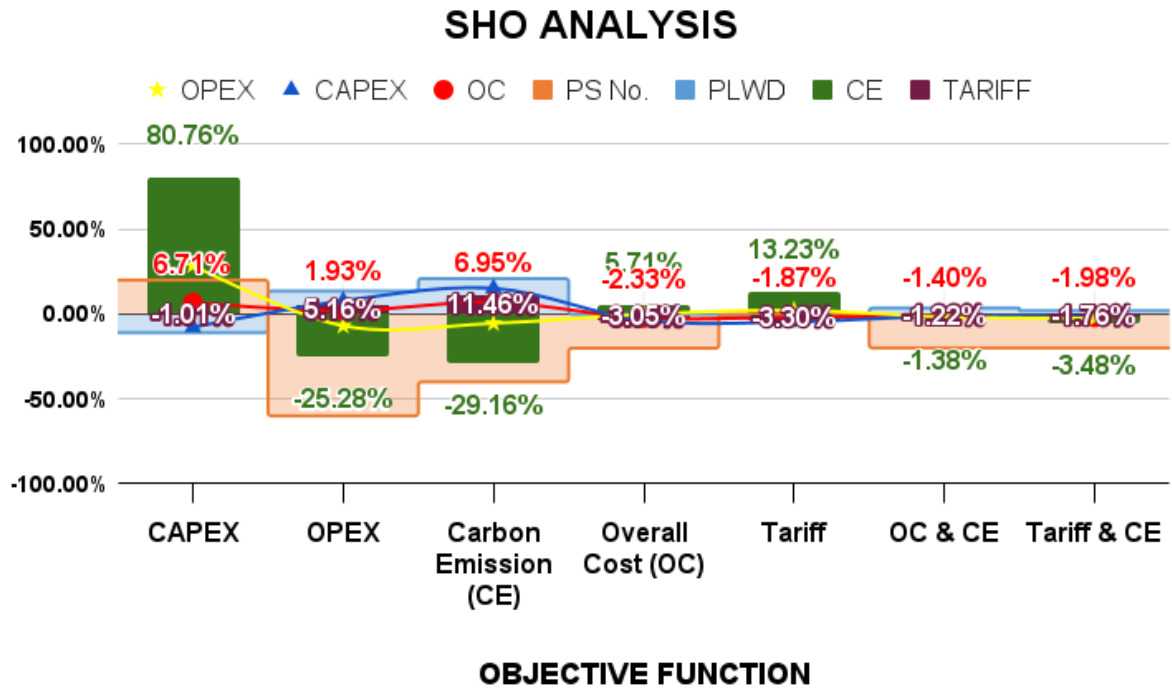


FIGURE 5.10: SHO Performance for different Objective Functions

TABLE 5.4: Impact of Objective Functions on CMPL SHO

Objective Function	PLWD (in inch)	PS No.	CAPEX (in B INR)	OPEX (in B INR)	OC (in B INR)	Tariff (in INR / MT)	CE (in CO2 GT)
Ref. PNC	15.18"	5	36.35	24.09	60.44	1138	616
CAPEX	13.52"	6	33.51	30.99	64.49	1126	1113
OPEX	17.24"	2	39.19	22.41	61.60	1126	460
CE	18.36"	3	41.86	22.77	64.64	1268	436
OC	15.17"	4	34.99	24.04	59.03	1103	651
Tariff	14.97"	5	34.66	24.64	59.30	1100	697
OC & CE	15.72"	4	35.92	23.67	59.59	1124	607
Tariff & CE	15.48"	4	35.75	23.49	59.24	1118	594

5.1.3.1 Mono Objective Functions

CAPEX: It is noteworthy that relying exclusively on CAPEX performance parameter in the objective function is a common practice among pipeline design engineers and may indeed primarily align with the investment optimization goals of the pipeline owner only. However, it could inadvertently impose a significant burden on end customers in terms of elevated operating costs and place undue stress on the environment. As highlighted in Table 5.4, when the objective function is CAPEX-based, the resulting PNC exhibits the lowest CAPEX value at 33.51 Billion INR. However, this benefit is offset by a significant 28.63% increase in operational expenses (OPEX). Consequently, this leads to the second-highest overall cost increase, amounting to 64.49 Billion INR (6.71%), and the third-largest tariff value at 1126 INR/MT (-1.01%). Hence, it is essential to recognize that while both overall cost and tariff serve as indicators of commercial aspects, they exhibit differing sensitivities to variables and performance parameters. Furthermore, a significant observation emerges from a reduction in PLWD by -10.94% with the addition of an extra pumping station. This decrease suggests a shift towards the utilization of smaller pipe diameters, thereby necessitating more pumping stations. However, it is crucial to consider the broader implications of this choice, particularly regarding environmental concerns. The CAPEX-based PNC exhibits the highest increase in carbon emissions, surging by 80.76%. Therefore, within the broader TEC context, it becomes evident that relying solely on CAPEX as the only performance parameter in the objective function is not a recommended practice.

During the CAPEX-based SHO, it is found that the proposed framework, inspired by real-world industrial practices, presents significant untapped potential for further optimization by considering the possibility of constructing intermediate pumping stations at SV and IPS nodes. In the context of the considered case study, especially with the CAPEX-based objective function, a notable outcome was observed: the construction of pumping stations at nodes 3, 6, and 12, a result that previous research frameworks might have missed. This emphasizes the proposed framework's capability to reveal more valuable and previously unexplored optimization-efficient solutions.

OPEX: Although it is uncommon to consider OPEX as the exclusive objective function in PNC design optimization, this approach is commonly adopted to address post-commissioning operational challenges in the pipeline industry. The OPEX objective function presents a unique dynamic, often engaging in trade-offs with CAPEX performance parameters, resulting in diverse PNC outcomes. Remarkably, the OPEX-based objective function yields the second-highest increase in PLWD at 13.52%, achieved with only two pumping stations, including the dispatch

station. It is important to recognize that opting for a larger diameter upfront may not always be the most prudent strategy to effectively mitigate design risks, especially in scenarios where significant demand volume variations are anticipated. As expected, this approach leads to the lowest overall OPEX value (22.41 Billion INR), albeit with the second-highest increase in CAPEX to 39.19 Billion INR (7.82%). Consequently, there is a comparable increase in the overall cost, amounting to 61.61 Billion INR (1.93%). Furthermore, the impact on tariff and carbon emission contrasts with that of the CAPEX-based objective function. In this case, the PNC outcome demonstrates the second-largest increase in tariff of 1197 INR/MT (5.16%) but also records the second-largest reduction in carbon emissions by 156 CO₂ GT (-25.28%). It is essential to acknowledge that the performance parameters of tariff and carbon emissions exhibit higher sensitivity to PNC outcomes compared to the overall cost. Therefore, the evaluation of these parameters should be conducted to capture even minor impacts of design variations. The sensitivity analysis of the mono-objective functions in PNC design optimization inferred that relying solely on CAPEX or OPEX does not yield a balanced PNC solution that fully accounts for the complete TEC aspects. A combination of both parameters is necessary to achieve this balance, as discussed in the following sections.

5.1.3.2 Mono-to-Multi Objective Functions

Carbon-emissions: This study pioneers the examination of pipeline project carbon emissions as the singular objective function in PNC design optimization, encompassing elements from both pipeline construction and operations. The findings highlight the potential for achieving a remarkable reduction of 180 CO₂ GT (-29.16%) compared to the reference PNC but at the cost of a notable 11.46% increase in tariff value. The resulting performance parameters are similar to those derived from an OPEX-based objective function, although OPEX-based functions typically yield better commercial outcomes. Furthermore, this approach prioritizes the diameter decision variable over the number of pumping stations. Therefore, similar to the mono-objective function, carbon emissions should be considered alongside other performance parameters within a broader multi-objective function methodology. This ensures a more comprehensive evaluation and equilibrium across TEC aspects of PNC design optimization.

Overall Cost: Optimizing the overall cost objective function remains a conventional and prevalent practice in both PNC design optimization literature and industry applications. This approach distinguishes itself from other objective functions by achieving a significant reduction in both decision variables - PLWD and the number of pumping stations. Through an amalgamation of the CAPEX and OPEX metrics into an integrated objective function, it effectively addresses

their inherent trade-off dynamics. As a result of this trade-off optimization, with CAPEX decreasing by -3.75% and OPEX by -0.19%, the overall cost is minimized to 59.03 billion INR, representing a -2.33% reduction, with a more prominent contribution from the CAPEX components. Further, this reduction in CAPEX leads to lower initial-year cash flows, resulting in the second-lowest tariff at 1103 INR/MT (-3.05%). It's essential to acknowledge that this approach triggers an increase in carbon emissions by 5.71%. Therefore, it becomes imperative to consider this trade-off in conjunction with carbon emissions within a multi-objective function called Overall-cost & Carbon-emissions based Multi-Objective Function (OCMOF). This combined approach ensures a balanced and sustainable outcome, considering the broader spectrum of environmental and economic aspects in PNC design optimization.

Tariff: Tariff considerations are of paramount importance in the practical design of PNCs, aligning with regulatory requirements from a financial perspective. This research introduces a novel approach by incorporating tariff-based performance parameters, providing a thorough evaluation of financial considerations. In addition to year-wise CAPEX and OPEX components, it encompasses other crucial financial factors such as EPMC cost (C_{EP}), start-up commissioning & owner expenses (C_{SO}), EIA studies cost, mitigation cost (C_{EN}), contingency cost (C_C), and spare cost (C_{SP}). Additionally, it accounts for the implications of demand volume escalation, thus enriching the optimization process, as detailed above. This approach results in a -1.42% reduction in PLWD, while the number of pumping stations remains consistent with the reference PNC. The outcome shares similarities with the overall cost-based objective function, except for OPEX, which experiences a 2.29% increase. The tariff-based objective function fulfils the regulator's requirement of achieving a minimum tariff value of 1100 INR/MT, thereby ensuring the lowest possible transportation tariff and its consequential positive impact on the ultimate market price of the product. However, it's essential to recognize that the tariff-based objective function does entail a trade-off, resulting in higher carbon emissions (13.23%). Therefore, as an extension of the research objective, it becomes imperative to consider this in conjunction with the carbon emissions performance parameter as part of a more comprehensive Tariff & Carbon-emissions-based Multi-Objective Function (TCMOF), akin to OCMOF.

5.1.3.3 Multi Objective Functions

Overall Cost and Carbon-emission: The objective functions based on overall cost and carbon emissions demonstrate a trade-off relationship, making them indispensable for addressing the complete requirements of TEC aspects. Within the framework of the OCMOF, the optimizer achieves a significant reduction in carbon emissions by -1.38%, resulting in a more environmentally friendly PNC outcome in comparison to reference PNC. However, this accomplishment

is accompanied by heightened commercial performance parameters, notably an increase of 560 Million INR (1%) in overall cost and tariff increment by 21 INR/MT (1.9%) with respect to the overall cost-based objective function results. Moreover, all commercial-environmental outcomes are still better than reference PNC. It is also observed that this reduction in carbon emissions is facilitated by a slight increase in PLWD while maintaining the same number of pumping stations observed in the overall cost-based objective function. This suggests that the OCMOF has the potential to offer a better balance between financial and environmental aspects in PNC design optimization.

Tariff and Carbon-emission: In the optimization process of PNC, it's vital to consider the tariff performance parameter alongside carbon emissions to ensure a balanced approach. The Tariff & Carbon-emission based Multi-objective Function (TCMOF) plays a key role in avoiding undue financial burdens on users due to increased OPEX while also addressing environmental concerns observed in the tariff-based objective function. The TCMOF optimizer achieves this objective by slightly increasing the PLWD while simultaneously reducing the number of pumping stations. Remarkably, the TCMOF yields the most robust, balanced, and sustainable solution across all TEC performance parameters, even outperforming the OCMOF with reduced CAPEX, OPEX, Overall-cost, Tariff & carbon-emissions by -0.47%, -0.78%, -0.59%, -0.55% & -2.18% respectively (as detailed in Table 5.4). Therefore, TCMOF takes precedence in the subsequent sections, facilitating a comprehensive examination of its impact on performance parameters across various types of Multi-Horizon Optimization (MHO) frameworks employed for problem statements with variable demand volume.

The summary of the Objective Function Sensitivity Analysis outcomes is as follows:

1. Each performance parameter excels within its corresponding objective function.
2. In the CAPEX-based Objective Function, new IPPS nodes (3, 6, and 12) are identified at intermediate stations, which would be overlooked by traditional methodologies.
3. The trade-off relationship between decision variables is confirmed. As the pipeline diameter (PLWD) increases, the number of pumping stations decreases, and vice-versa. Similarly, the trade-off relationship between CAPEX and OPEX performance parameters is also re-verified.
4. There is a direct relationship between CAPEX and PLWD, with a strong correlation coefficient of 0.98. This means that as PLWD increases, CAPEX increases and OPEX decreases. A similar direct relationship between OPEX and the number of pumping stations is also established, with a correlation coefficient of 0.84.

5. Mono-objective Functions: It is not recommended to consider either of the Mono-objective functions (CAPEX or OPEX) alone due to their trade-off relationship, as this would result in biased outcomes favouring one decision variable over the other.
6. Mono-to-Multi Objective Function & Multi-objective Functions: To ensure sustainable balanced development, it is recommended to consider both types of Mono-to-Multi Objective Functions (tariff/overall-cost for commercial, and carbon-emissions for environmental) combined in Multi-objective Functions.
7. The TCMOF provides slightly better performance parameters compared to other multi-objective functions of OCMOF.

5.1.4 SHO & MHO Outcome: Central India Pipeline

A prominent Indian Oil Marketing Company had initiated an important pipeline project involving the construction of a 356-kilometer-long cross-country multi-product Central India Pipeline (CIPL). This pipeline is engineered with an 18-inch diameter, featuring an average design safety factor of 0.65 and a single pumping station at the dispatch location. It is designed to transport MS and HSD, with an expected gradual increase in total demand volume from 2.2 MMTPA to 3.4 MMTPA over the 13 years from the commissioning. Subsequently, the demand volume remains consistent for another 11 years of the designated time horizon. It's important to emphasize that the information about the project, obtained from publicly available data, is solely intended to establish the research problem statement. This study does not aim to challenge the decisions made by the project's pipeline design engineers but rather aims to equip future pipeline design engineers with a reliable and supportive PNC design tool. The project's performance parameters are based on the TEC models proposed in this study, with initialization inputs sourced from [135], targeting an IRR of 12%. The evaluated values of these performance parameters for the given inputs are detailed in Table 5.5, with the graphical representation of the reference PNC illustrated in Figure 5.11 using graphical notation.

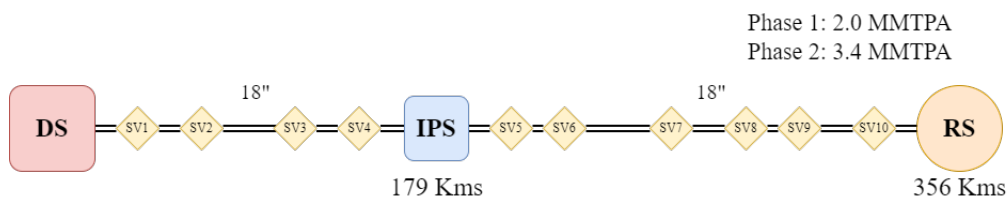


FIGURE 5.11: CIPL Reference PNC

It's important to highlight a fundamental difference between the current CIPL problem statement and the previous CMPL scenario used in various previous literature SHO analyses: the CIPL features varying volume and elevation profiles. This real-world context introduces a distinct dimension to the study, shedding light on the practical intricacies and dynamics inherent in PNC design. With 12 locations/nodes and 12 pipeline sections, each offering a selection from 5 different commercial diameters based on velocity boundary limits, the problem becomes computationally intensive, with a staggering 317 crore potential combinations. The CIPL problem, encompassing all 24 decision variables, serves to further assess the efficacy of the proposed SHO framework and evaluate different types of MHO frameworks by comparing their outcomes with actual CIPL PNC performance parameters. The results obtained from various methodologies are summarized in Table 5.5 and thoroughly discussed below.

5.1.4.1 CIPL SHO outcome:

In the assessment of the SHO outcomes for the CIPL, the demand volume for the final year across the entire time horizon is taken into account. Through this analysis, it's observed that incorporating a pumping station at node 8 (SV6) results in a considerable reduction in pipeline diameter, decreasing it to 14 inches (-22.22%) along its entire length. This strategic adjustment in the PNC results in substantial overall cost savings for the owner, amounting to -4.9% (equivalent to 1.06 Billion INR), and a considerable decrease in tariffs for the regulator, with a notable -14.5% reduction (by 123 INR/MT). While this optimization strategy offers compelling financial advantages, it's important to note the significant increase in carbon emissions, surging significantly by 178.7% (equivalent to 200 CO₂ GT). Given the demand volume variations in the CIPL, rendering its SHO outcome suboptimal, essentiate to conduct MHO analysis for this problem statement.

5.1.4.2 PSMHO outcome:

In the PSMHO framework, the PNC outcome reflects that of the SHO, with the postponement of the installation of IPPS in the 7th year post-commissioning. This strategic manoeuvre not only drives further reductions in overall costs for the owner by a substantial -5.61% (equivalent to 1.21 Billion INR), and decreases in tariffs for the regulator, with a notable -16.47% reduction (by 139 INR/MT), but also results in slightly lower carbon emissions, totalling 309 CO₂ GT (-1%) in comparison to SHO outcome. These results highlight the effectiveness of the PSMHO framework in achieving a well-balanced TEC solution.

5.1.4.3 PLMHO outcome:

Comparing PSMHO phasing to pipeline laying phasing reveals challenges due to various external factors such as social, political, environmental, and regulatory factors. Therefore, for the CIPL problem statement, the two-stage PLMHO framework is considered. Additional analysis of the PLMHO framework has been conducted to examine the impact of phasing year on the outcome, as depicted in Figure (5.12). Overall, implementing PLMHO generally reduces tariff rates, but in certain cases, it may increase overall costs. The carbon emissions parameter consistently shows a strong correlation with the number of intermediate pumping stations, reaching notably high values at the extremes of the analysis period due to potential overdesign of the PNC for either period. Notably, in the 7th year, when the initial phase constitutes approximately 80% of the total volume, PLMHO emerges as the most economically and environmentally viable solution with the lowest number of pumping stations. This approach results in a marginal reduction in overall costs (-0.26%) and a significant decrease in tariff (-8.76%). Although it is still associated with higher carbon emissions of 191 CO₂ GT compared to the original CIPL outcome, it is worth noting that this approach results in the second-lowest carbon emissions among the various optimization methodologies analysed.

The PLMHO approach inherently achieves SHO outcomes as the demand volume approaches its final value. In the CIPL problem statement, the PLMHO-derived SHO (PLMHO-SHO) PNC outcome features 16-inch diameters across all sections without pipeline laying phasing and intermediate pumping stations. The PLMHO approach exhibits a tendency to favour higher PLWD, as observed when its outcome is compared to SHO results. This results in the lowest overall cost of 19.86 billion INR, albeit with a 4.22% higher tariff value compared to the SHO outcome (but still 10.8% lower than the original PNC). Importantly, the PLMHO framework delivers PNC outcomes with the lowest carbon emission value of 158.76 CO₂ GT among all other methodologies, offering significant environmental benefits.

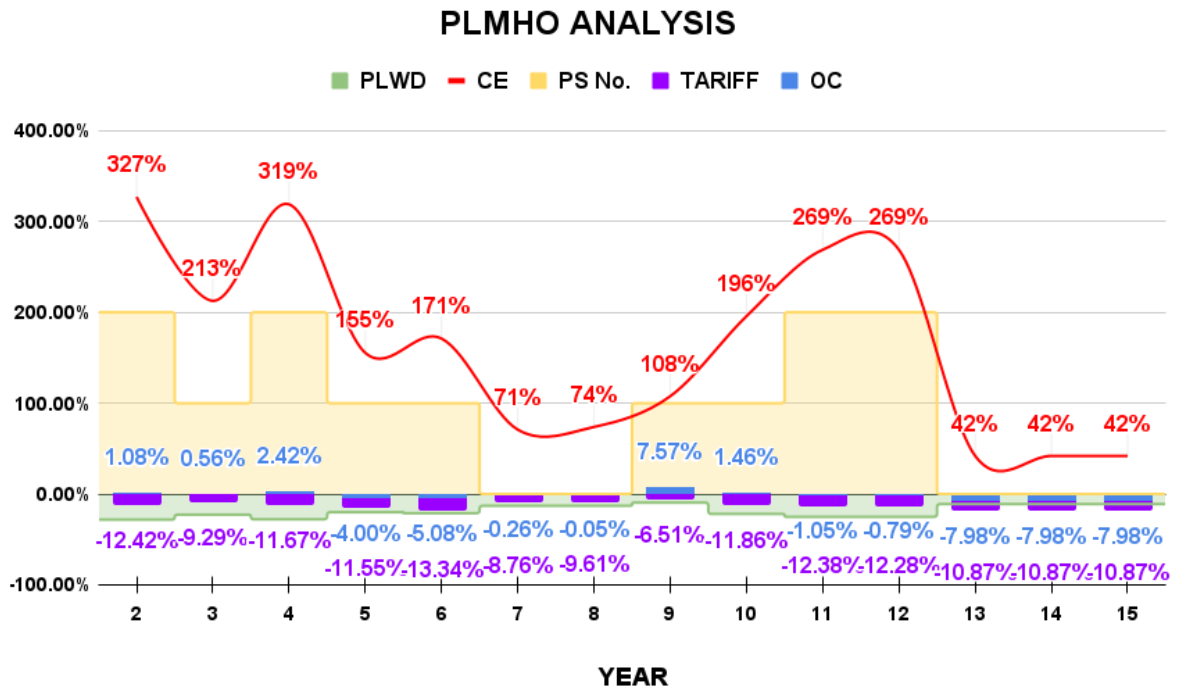


FIGURE 5.12: Impact of Initial Phasing Year Selection on PLMHO

5.1.4.4 PLPSMHO outcome:

The optimal PNC outcome achieved using the PLMHO methodology was observed in the 7th year due to the rapid growth in demand volume within a relatively short timeframe. However, it's worth mentioning that the frequent laying of parallel pipelines across mainline sections within such a short period is not typical in industrial practice. Therefore, for the examination of the PLPSMHO framework, the 11th has been selected as the timeframe for laying parallel pipelines across the mainline sections. In comparison to the PLMHO outcome in the 11th year, the PLPSMHO framework schedules the construction of intermediate pumping stations at the nodes 4 & 9 in the 3rd & 10th respectively. This results in a modest reduction in overall cost of -0.41% (87 Million INR), but a more substantial decrease in tariff rates by -3.85%, and a -1.34% reduction in carbon emissions. When compared to the most optimal outcome of the PLMHO framework achieved in the 7th year, it's noteworthy that although the PLPSMHO approach exhibits higher carbon emissions, it achieves reductions in overall cost and tariff rates by -1.19% and -7.66%, respectively.

TABLE 5.5: CIPL PNC performance for different MHO Frameworks

PNC Case	PLWD (in inch)	PS No.	Overall Cost (in B INR)	Tariff (in INR/MT)	CE (in CO2 GT)
Original PNC	18.00"	1	21.58	846	112
SHO	14.00"	2	20.52	724	312
PSMHO	14.00"	2	20.37	707	309
PLMHO (n=7)	15.68"	1	21.53	772	191
PLMHO (n=11)	13.48"	3	21.36	741	412
PLMHO-SHO (n=13)	16.00"	1	19.86	754	159
PLMHO-SHO (n=11)	13.48"	3	21.27	713	407

Below is a summary of the impact of SHO and MHO on the CIPL case study:

1. **SHO:** Compared to the original PNC, SHO introduces an intermediate pumping station, which results in a decrease in the pipeline diameter (PLWD). This PNC improves the commercial performance parameters, achieving a tariff reduction of 14%, but it comes at the expense of higher carbon emissions.
2. **PSMHO:** The outcome is similar to that of SHO, with the addition of phasing the intermediate pumping station to the seventh year. This results in improvements across all performance parameters of SHO, including a reduction in carbon emissions.
3. **PLMHO:**
 - Sensitivity analysis of the two-stage PLMHO for the CIPL problem suggests initiating the first phase of the PNC design when demand reaches 80% of total volume.
 - PLMHO responds similarly to SHO when the final demand volume is considered in the first phase. It has been found that PLMHO achieves a smaller PLWD while maintaining the same number of pumping stations resulting in a 9% reduction in costs, indicating that the original model is overdesigned.
 - Compared to PSMHO, PLMHO showed reduced commercial performance parameters, except for the reduction in carbon emissions.
4. **PLPSMHO:** PLMHO for the eleventh year is considered for the analysis in which PSMHO optimizer phased its intermediate pumping stations construction to the 3rd and 10th year. This results in an improvised outcome of PLMHO, hence it is recommended that PSMHO should be applied on PLMHO outcomes with an intermediate pumping station(s).

Chapter 6

CONCLUSION

6.1 CONCLUSION

The research offers a comprehensive and innovative methodology for modelling liquid pipelines, addressing key techno-commercial-environmental aspects crucial for practical pipeline design, construction, and operation. By critically examining previous research and identifying gaps, it emphasizes the necessity for a more holistic framework that encompasses all critical factors of pipeline modelling and its optimization. This proposed framework integrates hydraulic analysis, regulatory requirements, physical constraints & boundary conditions, and economics essential for practical pipeline network design. Additionally, it introduces novel performance parameters, including pipeline transportation tariffs and comprehensive carbon emissions, catering to the interests of all stakeholders and end-customers alike. For the first time, concepts such as dynamic carbon emissions, linefill costing, tariff computation, and project phasing are introduced and their impact on performance parameters is thoroughly discussed. This research contributes significantly to the field of liquid pipeline modelling, offering a more practical and comprehensive approach. Furthermore, this work lays the groundwork for future research to further refine pipeline modelling approaches. The proposed optimization framework along with new performance parameters & objective functions have the potential to revolutionize the pipeline industry, promoting fair, efficient, and sustainable pipeline transportation.

The technical modelling of the China Multi-product Pipeline (CMPL) serves as a base case study in this research for modelling. The hydraulic results from the proposed model are validated against the Pipeline Studio software outcomes for the same modelling inputs, demonstrating a high level of accuracy with an overall median deviation of 0.3% and an acceptable range of 1.1% deviation, with the exception of the suction pressure at the end RS location. Subsequently, a

sensitivity analysis is conducted on various modelling components to explore their impact on the performance parameters, revealing that changes in elevation, temperature, and volume growth rate not only influence these outcome performances but may also render the original solution infeasible. Thus, it emphasizes the importance of considering these components during pipeline modelling to derive realistic and feasible solutions.

Based on identified research gaps and further empirical analysis, several recommendations are proposed for future PNC models with the aim to enhance the accuracy, efficiency, and sustainability of pipeline projects while addressing diverse stakeholder interests:

1. It is foremost to consider the pipeline route terrain inputs as they profoundly influence both hydraulic feasibility & cost. It's crucial to account for the influence of the type of ROU on the cost of both the mainline pipeline (laying and compensation) and land procurement for stations.
2. Thermal effects have a significant impact on pipeline stability and hydraulic feasibility. Therefore, it is essential to verify whether the pipeline can withstand the extreme temperatures to which it may be exposed. For liquid pipelines, it is advisable to account for the minimum product temperature in each section to ensure comprehensive safety and reliability.
3. To ensure a reliable and precise PNC design, it is advisable to select a discrete pipeline diameter according to standard recommendations and commercial availability. This research further discusses regulatory and best engineering practices, such as setting boundary limits for pipeline thickness & velocity, constructing IPS & SV stations, and determining tankage requirements for contingency sales & interface mitigation.
4. The PNC model must account for dynamic demand volume due to its impact on pipeline hydraulics and cost. For minor variations, design margins can be incorporated, such as the 5% margin in discharge pressure used in this study. Similarly, tankages are to be designed for additional storage margin for seasonal fluctuations and maintenance shutdowns to ensure uninterrupted supply chain operations. For forecasted demand volume, project phasing is recommended to address the predominant issue of pipeline underutilization, balancing performance parameters with demand volume uncertainty. It's also crucial to adhere to practical project timelines, as delays can affect the tariff by up to 26%.
5. The research offers comprehensive details on the CAPEX and OPEX components, along with the impact of their rate changes. Key cost factors, which are missing in previous

literature, such as fixed CAPEX components, linefill cost, tankage cost, and OPEX escalation must be considered, as they can significantly affect the overall project cost by up to 23%. Therefore, it is essential to account for these cost factors in the cost modelling to ensure accurate cost estimation and effective decision-making during pipeline design and operation.

6. To achieve a balanced approach that considers the interests of both users and end-customers, it's essential to incorporate pipeline tariff calculation, covering all commercial aspects of pipeline design, construction, and operations. Technically, the tariff is influenced by numerous variables and parameters across the pipeline lifecycle, ensuring more precise and reliable outcomes.
7. In light of mounting concerns about climate change, especially regarding hard-to-abate industries like petroleum, it's imperative to prioritize a balanced commercial-environmental approach in PNC design. Therefore, the calculation and integration of carbon emissions should be fundamental to projects. From a technical standpoint, akin to tariff considerations, carbon emissions assessment encompasses all PNC components across the pipeline's lifespan, albeit with distinct constituent elements. Moreover, it's advisable to account for dynamic carbon emission coefficients during pipeline operations, aligning with the owner's and government's commitments to reducing carbon emissions.

This research aimed to formulate a comprehensive methodology for pipeline modelling and to establish an optimization-centric framework to tackle several crucial challenges. While various optimization techniques are available, the consideration of a stochastic technique has steered the solution strategy, given the recognition that such optimizers are adept in managing the multitude of constraints inherent in MINLP problem formulations. Appropriate optimizers within the Python environment were selected to implement this methodology. Further, it highlights the ever-evolving landscape of pipeline construction and the multitude of factors influencing decision-making processes. Through the analysis of various objective functions, it provides extensive insights into their effects on performance parameters. By methodically assessing different methodologies, stakeholders can make well-informed decisions that maintain a balance between financial, environmental, and operational considerations in pipeline network design. Ultimately, the proposed PNC design optimization framework contributes to the successful and sustainable development of pipeline systems, fulfilling the needs of owners, users, and regulators.

During the investigation of the CMPL SHO study, a thorough sensitivity analysis of different objective functions on the performance parameters has unveiled several noteworthy findings mentioned below:

1. **Advanced PNC Design Optimization:** The notable results demonstrate the potential for achieving significant additional reductions in CAPEX, OPEX, and overall costs compared to the already optimized reference PNC presented in the previous literature work, resulting in remarkable savings for the owner of up to 2.84 billion INR, 1.68 billion INR, and 1.41 billion INR in the respective performance parameter. Additionally, there is a substantial decrease in tariff rates by 38 INR/MT over the analysis period, along with a significant reduction of 180 CO₂ GT in carbon emissions, effectively aligning with regulatory and carbon emission reduction requirements.
2. **Diverse Sensitivity Metrics:** Despite both overall cost and tariff being associated with commercial aspects, they showcase distinct sensitivities to different variables and performance parameters. This underscores the necessity of employing various objective functions in optimization to suit project-specific objectives. Moreover, tariff and carbon emission performance parameters have displayed greater responsiveness in sensitivity analysis compared to traditional metrics like CAPEX, OPEX, and overall cost. This characteristic makes them particularly suitable for future sensitivity studies in the design of PNC.
3. **Optimizer Search Space Expansion:** Inspired from real industrial practices, the proposed framework has unveiled substantial untapped potential within previously optimized reference PNCs. This is achieved by expanding the search space of the optimizer to encompass the entire spectrum of available commercial diameters, alongside considering velocity boundary conditions. Additionally, the framework explores the viability of intermediate stations such as SV and IPS for the construction of intermediate pumping stations. This revelation is observed particularly in the case study of the CAPEX-based objective function, where intermediate SV station nodes 3, 6, and 12 in the base model are considered for pumping stations during optimization, which may have been overlooked in previous research frameworks.
4. **Performance Parameters Correlations:** Notably, OPEX and carbon emissions exhibit a direct correlation with pipeline diameter (PLWD) decision variables, whereas CAPEX and tariffs are associated with the number of pumping station decision variables. An evident reverse relationship is observed between these decision variables also. These correlations highlight the complex interconnections among different performance parameters during PNC design.
5. **Advancing Sustainable Development via Multi-Objective Optimization:** The proposed optimization framework effectively balances commercial (tariff) and environmental (carbon emissions) performance parameters, yielding promising sustainable results for future pipeline projects. This approach shows that PNC designers can significantly reduce

TABLE 6.1: Impact of TCMOF

Objective Function	PLWD (inch)	PS (No.)	CAPEX (B INR)	OPEX (B INR)	Tariff (INR/MT)	CE (CO2 GT)
Tariff	14.97"	5	34.66	24.64	1100	697
CE	18.37"	3	41.86	22.77	1268	436
Tariff + CE	15.48"	4	35.75	23.49	1118	594

carbon emissions over the pipeline's lifecycle with minimal impact on commercial performance. Below is a comparison table illustrating the optimization outcomes of different types of objective functions, including tariff, carbon emission, and combined results in 6.1:

To explore the effectiveness of MHO, this study scrutinizes a case study involving the Central India Pipeline (CIPL), characterized by varying demand and elevation profiles. Prior research has not extensively covered these methodologies, rendering this study both a resource for future reference and an evaluation of their efficacy in real-world scenarios. Below is a concise overview of the examinations conducted for CIPL Single-Horizon Optimization (SHO) and Multi-Horizon Optimization (MHO):

1. **SHO Sub-optimality:** With the variations in demand volumes, it becomes evident that the SHO provides a suboptimal outcome, prompting a thorough examination of various MHO frameworks. In the CIPL case study, the Pumping Station Multi-Horizon Optimization (PSMHO) exhibits superior Techno-Economic Environmental (TEC) results compared to the SHO approach by strategically phasing the installation of intermediate pumping stations in the 7th year. In comparison to the original CIPL PNC, PSMHO illustrates notable reductions in overall cost and tariff rates, with decreases of -4.90% and -14.48%, respectively.
2. **Effect of Phase Selection in PLMHO:** The research assesses the implementation of the two-stage Pipeline Laying Multi-Horizon Optimization (PLMHO) on the CIPL problem statement. It is noted that to attain a well-balanced TEC result, the initial phase year for PNC design optimization should be chosen when demand volumes reach approximately 80% of the total demand.
3. **Integrated PLMHO and PSMHO Framework:** The PLPSMHO optimization framework demonstrates significant cost savings of 87 million INR for the owner, along with a noteworthy reduction of -3.85% in tariff rates in comparison to singular PLMHO framework for the same final PNC involving pipeline laying in the eleventh year by phasing the

construction of intermediate pumping stations. Additionally, it achieves a commendable reduction of 6 CO₂ GT in carbon emissions.

4. **Standardizing Tariff Calculation:** Throughout the various PNC design optimization frameworks explored, enhancements in tariff assessment consistently emerged across all findings. This emphasizes the critical necessity for regulators to establish standardized tariff calculation protocols, thereby mitigating unwarranted burdens on both pipeline users and end consumers. Previous studies, to our knowledge, have not delved into the optimization problem while considering the regulatory agency's concerns and representation of the public interest. In this regard, the primary novelty of this study lies in formulating the optimization problem to ensure that the project is structured in a manner that aligns with various facets of public interest as regulations stipulated by regulatory bodies.

5. **Advantages of Superiority System-based Techniques over Heuristic Methods:** As the complexity of the problem escalates, heuristic human-based approaches become less effective in identifying optimal solutions. On the other hand, the algorithm's effectiveness in achieving competitive cost reductions improves with the complexity of the network. A single execution of a developed algorithm on a basic computer with 8GB RAM and an i5 core processor takes mere minutes, contrasting with the at least a day-long duration required by an average engineer for a comparable procedure. Results indicate that the algorithm consistently outperforms heuristic methods, yielding tariff reductions of up to 16% compared to the minimum network cost obtained through heuristic approaches. While this solution offers a near-global optimum, the algorithm consistently delivers high-quality solutions accompanied by substantial cost and carbon emissions reductions.

Essentially, this study not only uncovers the significant untapped potential for optimizing pipeline networks but also emphasises the importance of selecting the most suitable objective functions and frameworks to maintain a balance between commercial viability & environmental sustainability in real-world pipeline design scenarios. The proposed framework offers a precise and dependable approach to address the PNC optimization problem, encompassing strategic pumping station placement, optimal pipeline laying phasing periods, and adherence to regulatory requirements. Consequently, regulatory authorities can utilize this tool to assess permissible tariff rates in the public's best interest. Therefore, this research lays the groundwork for future optimization endeavours, as the proposed framework can be further refined with forthcoming more advanced optimizers to yield even deeper insights and can be extended to tackle more intricate & challenging problem statements, ensuring both commercial effectiveness and environmental sustainability.

6.2 FUTURE WORK

Future research efforts aim to tackle the following areas, advancing the field of PNC design optimization and contributing to pioneering solutions for the pipeline industry:

1. Firstly, investigating the impact of alternative optimization algorithms beyond BPSO and GA could provide valuable insights into their efficacy and suitability for different PNC design scenarios. Algorithms such as simulated annealing, differential evolution, or hybrid approaches can offer novel perspectives and potentially superior solutions.
2. Secondly, extending optimization efforts to encompass modelling and optimization of natural gas pipeline networks, particularly for City Gas Distribution (CGD) networks. CGD networks present unique challenges and opportunities due to their complex network structures, varying demand, network topology, and infrastructure constraints. Future research could focus on developing specialized optimization methodologies tailored to the specific characteristics of CGD networks, aiming to improve efficiency, reliability, and cost-effectiveness.
3. Thirdly, leveraging Geographic Information System (GIS) techniques for determining the optimal pipeline route and design safety factors can enhance the accuracy and efficiency of pipeline network design. GIS offers powerful tools for analyzing spatial data, terrain characteristics, environmental factors, and infrastructure constraints, enabling engineers to identify the most suitable route and optimize design parameters accordingly. For future work, it is recommended to integrate the algorithm with GIS-based simulation software and utilize multiprocessor computers. This would expand the study to tackle more complex problems involving a larger number of pipe elements and facilitate their implementation.
4. Finally, developing user-friendly front-end interfaces and software solutions for pipeline network optimization can facilitate broader adoption and implementation of optimization methodologies. This involves creating intuitive interfaces that allow users to input data, visualize results, and interpret findings easily. Moreover, filing patents for novel optimization techniques & software solutions and launching complete software packages can contribute to the advancement of PNC optimization.

These future directions hold promise for advancing the field of pipeline network optimization and addressing emerging challenges in the energy transportation sector.

Bibliography

- [1] Abebe, A. and Solomatine, D. (1998). Application of global optimization to the design of pipe networks. In *Proc. 3rd International Conference on Hydroinformatics, Copenhagen*, pages 989–996.
- [2] Adeyanju, O. and Oyekunle, L. A. (2013). Optimization of natural gas transportation in pipeline. *Department of Chemical Engineering, University of Lagos, Nigeria*.
- [3] Administration, N. E. (2015). *Design Code for Long-distance Oil and Gas Pipeline Engineering*. GB 50251. China Planning Press.
- [4] Ai, C., Zhao, H., Ma, R., and Dong, X. (2006). Pipeline damage and leak detection based on sound spectrum lpcc and hmm. In *Sixth International Conference on Intelligent Systems Design and Applications*, volume 1, pages 829–833.
- [5] Alam, M., Murshed, M., Palanisamy, D., Duraisamy, P., and Abduvaxitovna, S. (2023). Forecasting oil, coal, and natural gas prices in the pre-and post-covid scenarios: Contextual evidence from india using time series forecasting tools. *Resources Policy*, 81:103342.
- [6] Ali, A. (2022). Pre and post covid-19 disparity of financial performance of oil and gas firms: An absolute and relational study. *International Journal of Energy Economics and Policy*, 12:396–403.
- [7] American Petroleum Institute (2004). API 6h: Specification for end closures, connectors, and swivels. Technical report, American Petroleum Institute. <https://www.api.org>.
- [8] American Petroleum Institute (2013). API 1104: Welding of pipelines and related facilities. Technical report, American Petroleum Institute. <https://www.api.org>.
- [9] American Petroleum Institute (2014). API specification 6d: Specification for pipeline and piping valves. Technical report, American Petroleum Institute. [https://www.api.org/ /media/Files/Publications/14th](https://www.api.org/media/Files/Publications/14th)

- [10] American Petroleum Institute (2016). API standard 607: Fire test for quarter-turn valves and valves equipped with non-metallic seats. Technical report, American Petroleum Institute. <https://www.api.org>.
- [11] American Petroleum Institute (2018). API Specification 5L. *API Specification 5L* (online). <https://www.api.org/products-and-services/standards/important-standards-announcements/standard-5l>.
- [12] American Petroleum Institute (2019a). API 676: Positive displacement pumps - rotary. Technical report, American Petroleum Institute. <https://www.api.org>.
- [13] American Petroleum Institute (2019b). API rp 2218: Fireproofing practices in petroleum and petrochemical processing plants. Technical report, American Petroleum Institute. <https://www.api.org>.
- [14] American Petroleum Institute (2019c). API standard 6fa: Specification for fire test for valves. Technical report, American Petroleum Institute. <https://www.api.org>.
- [15] American Petroleum Institute (2020). API 675: Positive displacement pumps - controlled volume. Technical report, American Petroleum Institute. <https://www.api.org>.
- [16] American Petroleum Institute (2021). API 674: Positive displacement pumps - reciprocating. Technical report, American Petroleum Institute. <https://www.api.org>.
- [17] American Petroleum Institute (2023). API 610: Centrifugal pumps for petroleum, petrochemical and natural gas industries. Technical report, American Petroleum Institute. <https://www.api.org>.
- [18] American Society of Mechanical Engineers (2003). Valves—Flanged, Threaded, and Welding End. <https://www.asme.org/codes-standards/find-codes-standards/b16-34-valves-flanged-threaded-welding-endl>.
- [19] American Society of Mechanical Engineers (2017a). ASME b16.47: Large diameter steel flanges: Nps 26 through nps 60 metric/inch standard. Technical report, American Society of Mechanical Engineers. <https://www.asme.org/codes-standards>.
- [20] American Society of Mechanical Engineers (2017b). ASME b16.5: Pipe flanges and flanged fittings: Nps 1/2 through nps 24 metric/inch standard. Technical report, American Society of Mechanical Engineers. <https://www.asme.org/codes-standards>.
- [21] American Society of Mechanical Engineers (2019). ASME boiler and pressure vessel code, section viii, division 1: Rules for construction of pressure vessels. Technical report, American Society of Mechanical Engineers. <https://www.asme.org/codes-standards>.

- [22] American Society of Mechanical Engineers (2020). ASME b16.9: Factory-made wrought butt welding fittings. Technical report, American Society of Mechanical Engineers. <https://www.asme.org/codes-standards>.
- [23] American Society of Mechanical Engineers (2022). Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquid . <https://www.asme.org/codes-standards/find-codes-standards/b31-4-pipeline-transportation-systems-liquids-slurries>.
- [24] Andre, J. (2010). *Optimization of Investments in Gas Networks*. Thesis, Universite Lille Nord de France, Doctoral School in Business - Economics, Urban Planning and Management, Lille, France. <https://theses.hal.science/tel-00539689>.
- [25] Arya, A. K. (2021). Optimal operation of a multi-distribution natural gas pipeline grid: an ant colony approach. *Journal of Petroleum Exploration and Production Technology*, 11(10):3859–3878.
- [26] Arya, A. K. and Honwad, S. (2018). Multiobjective optimization of a gas pipeline network: an ant colony approach. *Journal of Petroleum Exploration and Production Technology*, 8(4):1389–1400.
- [27] Arya, A. K., Jain, R., Yadav, S., Bisht, S., and Gautam, S. (2022). Recent trends in gas pipeline optimization. *Materials Today: Proceedings*, 57:1455–1461.
- [28] Arya, A. K., Kumar, A., Pujari, M., and Pacheco, D. A. J. (2023). Improving natural gas supply chain profitability: A multi-methods optimization study. *Energy*, 282:128659. <https://doi.org/10.1016/j.energy.2023.128659>.
- [29] Association, C. S. (2019). *Oil and Gas Pipeline Systems*. CSA Z662. CSA Group, Toronto, ON.
- [30] Association, J. G. (2010). *Technical Standards for Gas Pipelines*. JGA TSG-11. JGA.
- [31] ASTM International (2009). ASTM D341-09: Standard Practice for Viscosity-Temperature Charts for Liquid Petroleum Products. Reapproved 2015.
- [32] Australia, S. (2018). *Pipelines: Gas and Liquid Petroleum*. AS 2885. Standards Australia, Sydney, Australia.
- [33] Azam, A. and Ahmad, N. (2023). Experience of financial health of select indian oil and gas companies by using zmijewski x-score model. *Catalyst Research*, 23:1438–1447.

- [34] Aziaka, D. S., Tukur, N., and Pilidis, P. (2019). Techno-economic evaluation of pipeline compression system: economic evaluation of the natural gas pipeline compression system-part 3. *International Journal of Mechanical Engineering and Technology (IJMET)*, 10:133–154.
- [35] Babu, K. J. and Vijayalakshmi, D. (2013). Self-adaptive pso-ga hybrid model for combinatorial water distribution network design. *Journal of pipeline systems engineering and practice*, 4(1):57–67.
- [36] Behrooz, H. A. (2019). A multiobjective robust approach for the design of natural gas transmission pipelines. *Chemical Product and Process Modeling*, 14(4).
- [37] Blank, J. and Deb, K. (2020). pymoo: Multi-objective optimization in python. *IEEE Access*, 8:89497–89509.
- [38] Borraz-Sánchez, C. and Haugland, D. (2011). Minimizing fuel cost in gas transmission networks by dynamic programming and adaptive discretization. *Computers & Industrial Engineering*, 61(2):364–372.
- [39] British Standards Institution (2005). BS 1873: Specification for globe and globe stop and check valves (flanged and butt-welding ends). Technical report, British Standards Institution. <https://shop.bsigroup.com/ProductDetail?pid=000000000030051569>.
- [40] Bureau of Indian Standards (2006). IS 8062-2: Cathodic protection of steel structures - code of practice, part 2: Underground structures. Technical report, Bureau of Indian Standards. <https://www.standardsbis.in>.
- [41] Bureau of Indian Standards (2018). IS 3043: Code of practice for earthing. Technical report, Bureau of Indian Standards. <https://www.standardsbis.in>.
- [42] Bureau of Indian Standards (2019). IS 2309: Code of practice for the treatment of water for generating steam for boilers. Technical report, Bureau of Indian Standards. <https://www.standardsbis.in>.
- [43] Cafaro, D. C., Presser, D. J., and Grossmann, I. E. (2022). Recent contributions to the optimal design of pipeline networks in the energy industry using mathematical programming. *Top*, 30(3):618–648.
- [44] CAG (2005). Report No. - 6 of 2005 for the period ended March 2004 Petroleum Sector. <https://saiindia.gov.in/en/old-audit-reports/view/13845>.
- [45] Carroll, L. and Hudkins, R. W. (2011). Advanced pipeline design.

- [46] Chebouba, A., Yalaoui, F., Smati, A., Amodeo, L., Younsi, K., and Tairi, A. (2009). Optimization of natural gas pipeline transportation using ant colony optimization. *Computers & Operations Research*, 36(6):1916–1923.
- [47] Chen, X., Wang, M., Wang, B., Hao, H., Shi, H., Wu, Z., Chen, J., Gai, L., Tao, H., Zhu, B., and Wang, B. (2023). Energy consumption reduction and sustainable development for oil and gas transport and storage engineering. *Energies*, 16(4):1775. <https://doi.org/10.3390/en16041775>.
- [48] Cheng, L. and Duran, M. (2003). World-wide crude transportation logistics: a decision support system based on simulation and optimization. *Proceedings Foundations of Computer-Aided Process Operations*, pages 187–201.
- [49] CIA (2021). Pipelines - the world factbook - cia.gov. <https://www.cia.gov/the-world-factbook/about/archives/2021/field/pipelines/>. [Accessed 03-06-2024].
- [50] Colebrook, C. F. (1939). Turbulent flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws. *J. Inst. Civ. Eng.*, 11(4):133–156.
- [51] da Silva Alves, F., de Souza, J. N. M., and Costa, A. L. H. (2016). Multi-objective design optimization of natural gas transmission networks. *Computers & Chemical Engineering*, 93:212–220.
- [52] Dale, S. (2023). bp Energy Outlook 2023 edition. *BP 2023* (online). <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2023.pdf>, year = 2023.
- [53] Dandy, G., Roberts, A., Hewitson, C., and Chrystie, P. (2006). Sustainability objectives for the optimization of water distribution networks. In *Proceedings of the 6th International Conference on Computing and Control for the Water Industry*.
- [54] Data, F. E. (2022). Federal reserve bank of st. louis. fred.stlouisfed.org.
- [55] de Rosa, G., Rodrigues, D., and Papa, J. (2019). Opytimizer: A nature-inspired python optimizer. *arXiv*.
- [56] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T. (2002). A fast and elitist multiobjective genetic algorithm: Nsga-ii. *Trans. Evol. Comp*, 6(2):182–197. <http://dx.doi.org/10.1109/4235.996017>.
- [57] Dey, P. K. (2004). Decision support system for inspection and maintenance: A case study of oil pipelines. *IEEE Trans. Eng. Manage.*, 51(1):47–56.

- [58] DOEA (2020). Report of the Task Force National Infrastructure Pipeline (NIP). <https://dea.gov.in/recentupdate/report-task-force-national-infrastructure-pipeline-nip-volume-ii>.
- [59] Douet, J. (2020). The heritage of the oil industry: Ticcih thematic study. *TICCIH*. <https://ticcih.org/wp-content/uploads/2020/07/Oil-industry-thematic-report.pdf>.
- [60] El-Mahdy, O. F. M., Ahmed, M. E. H., and Metwalli, S. (2010). Computer aided optimization of natural gas pipe networks using genetic algorithm. *Applied Soft Computing*, 10(4):1141–1150.
- [61] Elshiekh, T., A Khalil, S., and El Mawgoud, H. A. (2013). Optimal design and operation of egyptian gas-transmission pipelines. *Oil and Gas Facilities*, 2(04):44–48.
- [62] Eze, J. (2017). *Development of a Framework for Integrated Oil and gas Pipeline Monitoring and Incident Mitigation System*. PhD thesis, University of Wolverhampton. <http://hdl.handle.net/2436/620898>.
- [63] for Standardization, E. C. (2013). *Gas Supply Systems: Pipelines for Maximum Operating Pressure Over 16 Bar*. EN 1594. CEN, Brussels, Belgium.
- [64] for Standardization, I. O. (2017). *Petroleum and Natural Gas Industries: Pipeline Transportation Systems*. ISO 13623. ISO, Geneva, Switzerland.
- [65] for Water Resources, F. A. (2005). *Pipelines for the Transportation of Petroleum and Derivatives*. NBR 15280. ABNT.
- [66] für Normung, D. I. (2013). *Gas Supply Systems: Pipelines for Maximum Operating Pressure Over 16 Bar*. DIN EN 1594. Beuth Verlag.
- [67] GAD, A. A. M. and MOHAMMED, H. I. (2014). Impact of pipes networks simplification on water hammer phenomenon. *Sadhana*, 39(5):1227–1244. <https://doi.org/10.1007/s12046-014-0260-7>.
- [68] Galeano, H. and Narváez, P.-C. (2003). Genetic algorithms for the optimization of pipeline systems for liquid transportation (1). *CT&F-Ciencia, Tecnología y Futuro*, 2(4):55–64.
- [69] Garg, N., Rohtagi, A., Mittal, C., and Sharma, D. (2022). Combating workplace toxicity with the help of workplace spirituality: A study of indian public sector oil and gas companies. *International Journal of Public Administration*, 46:1–13.
- [70] Gazprom (2006). *Main Gas Pipelines. Design Standards*. STO Gazprom 2-3.5-051-2006. Gazprom.

- [71] GOI (1962). Pipelines and materials of construction act, 1962. Technical report, Government of India. <https://mopng.gov.in/files/TableManagements/Petroleum-and-Minerals-Pipelines-Act-1962.pdf>.
- [72] Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA.
- [73] Goldberg, D. E. and Kuo, C.-H. (1987). Genetic algorithms in pipeline optimization. *Journal of Computing in Civil Engineering*, 1(2):128–141.
- [74] Gu, L. (2021). Optimization of long-distance oil pipeline production operation scheme. In *IOP Conference Series: Earth and Environmental Science*, volume 772, page 012081. IOP Publishing.
- [75] Gupta, A. and Dalei, N. N. (2020). Energy, environment and globalization: an interface. In *Energy, environment and globalization*, pages 1–14. Springer.
- [76] Hajji, A. M. and Lewis, M. P. (2017). How to estimate green house gas (ghg) emissions from an excavator by using cat’s performance chart. In *AIP Conference Proceedings*, volume 1887, page 020047. AIP Publishing LLC.
- [77] Herrera-León, S., Lucay, F. A., Cisternas, L. A., and Kraslawski, A. (2019). Applying a multi-objective optimization approach in designing water supply systems for mining industries. the case of chile. *Journal of Cleaner Production*, 210:994–1004.
- [78] Hoel, L., Garber, N., and Sadek (2007). *Transportation Infrastructure Engineering: A Multimodal Integration*. General Engineering Series. Cengage Learning.
- [79] Holland, J. H. (1992). *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control and Artificial Intelligence*. MIT Press, Cambridge, MA, USA.
- [80] Hong, B., Li, X., Di, G., Li, Y., Liu, X., Chen, S., and Gong, J. (2019). An integrated milp method for gathering pipeline networks considering hydraulic characteristics. *Chemical Engineering Research and Design*, 152:320–335.
- [81] Huang, L., Liao, Q., Yan, J., Liang, Y., and Zhang, H. (2021a). Carbon footprint of oil products pipeline transportation. *Science of The Total Environment*, 783:146906.
- [82] Huang, L., Liao, Q., Yan, J., Liang, Y., and Zhang, H. (2021b). Carbon footprint of oil products pipeline transportation. *Science of The Total Environment*, 783:146906.
- [83] IEA (2020). Oil 2020 – analysis. <https://www.iea.org/reports/oil-2020>.

-
- [84] IEA (2021a). Key World Energy Statistics 2021. *IEA 2021* (online). <https://www.iea.org/reports/key-world-energy-statistics-2021>.
- [85] IEA (2021b). Oil 2021 - Analysis and forecast to 2026. *Oil 2021* (online). <https://www.iea.org/reports/oil-2021>.
- [86] IEEE Standards Association (2014). IEEE 519-2014: Ieee recommended practice and requirements for harmonic control in electric power systems. Technical report, IEEE Standards Association. <https://standards.ieee.org>.
- [87] Income Tax Department, G. o. I. (2022). Cost inflation index. [https://incometaxindia.gov.in/charts tables/cost-inflation-index.htm](https://incometaxindia.gov.in/charts%20tables/cost-inflation-index.htm).
- [88] Institution, B. S. (2015). *Code of Practice for Pipelines*. PD 8010. BSI, London, UK.
- [89] International Electrotechnical Commission (2010). IEC 61508: Functional safety of electrical/electronic/programmable electronic safety-related systems. Technical report, International Electrotechnical Commission. <https://www.iec.ch>.
- [90] International Electrotechnical Commission (2016). IEC 61511: Functional safety - safety instrumented systems for the process industry sector. Technical report, International Electrotechnical Commission. <https://www.iec.ch>.
- [91] International Electrotechnical Commission (2019). IEC 60079-11: Explosive atmospheres - part 11: Equipment protection by intrinsic safety "i". Technical report, International Electrotechnical Commission. <https://www.iec.ch>.
- [92] International Electrotechnical Commission (2020). IEC 60529: Degrees of protection provided by enclosures (ip code). Technical report, International Electrotechnical Commission. <https://www.iec.ch>.
- [93] International Electrotechnical Commission (2021). IEC 60034: Rotating electrical machines. Technical report, International Electrotechnical Commission. <https://www.iec.ch>.
- [94] International Organization for Standardization (2007). ISO 14313: Petroleum and natural gas industries - pipeline transportation systems - pipeline valves. Technical report, International Organization for Standardization. <https://www.iso.org/standard/41076.html>.
- [95] International Organization for Standardization (2016). ISO 21809-3: Petroleum and natural gas industries - external coatings for buried or submerged pipelines used in pipeline transportation systems - part 3: Field joint coatings. Technical report, International Organization for Standardization. <https://www.iso.org/standard/66868.html>.

- [96] Ivanik, S., Eroshkin, S., Koshelkov, I., and Shalygin, A. (2020). Development of an algorithm for determining the diameter and number of compressor stations of a gas pipeline in the c++ programming language. In *Journal of Physics: Conference Series*, volume 1661, page 012173. IOP Publishing.
- [97] Jakeš, J. (1988). A numerical method of fitting a multiparameter nonlinear function to experimental data in the l_1 norm. *Aplikace matematiky*, 33(3):161–170.
- [98] Jiao, K., Wang, P., Wang, Y., Yu, B., Bai, B., Shao, Q., and Wang, X. (2021). Study on the multi-objective optimization of reliability and operating cost for natural gas pipeline network. *Oil & Gas Science and Technology–Revue d’IFP Energies nouvelles*, 76:42.
- [99] Kabirian, A. and Hemmati, M. R. (2007). A strategic planning model for natural gas transmission networks. *Energy policy*, 35(11):5656–5670.
- [100] Kashani, A. H. A. and Molaei, R. (2014). Techno-economical and environmental optimization of natural gas network operation. *Chemical Engineering Research and Design*, 92(11):2106–2122.
- [101] Kennedy, J. and Eberhart, R. (1995). Particle swarm optimization. In *Proceedings of ICNN’95 - International Conference on Neural Networks*, volume 4, pages 1942–1948 vol.4.
- [102] Khanesar, M. A., Teshnehlal, M., and Shoorehdeli, M. A. (2007). A novel binary particle swarm optimization. In *2007 Mediterranean Conference on Control and Automation*, pages 1–6.
- [103] Khlebnikova, E., Sundar, K., Zlotnik, A., Bent, R., Ewers, M., and Tasseff, B. (2021). Optimal economic operation of liquid petroleum products pipeline systems. *AIChE Journal*, 67(4):e17124.
- [104] Kumar, A. (2016). Modeling, simulation, and optimization of a high-pressure cross-country natural gas pipeline: application of an ant colony optimization technique. *Journal of Pipeline Systems Engineering and Practice*, 7(1):04015008.
- [105] Lagutkin, M., Baranova, E. Y., and Balayan, É. (2021). An analysis of the influence of tube diameter on the capital and operating costs of a pipeline. *Chemical and Petroleum Engineering*, 56:710–714.
- [106] Li, Z., Liang, Y., Liao, Q., Zhang, B., and Zhang, H. (2021). A review of multiproduct pipeline scheduling: From bibliometric analysis to research framework and future research directions. *Journal of Pipeline Science and Engineering*.

- [107] Liang, J., Su, H., Sun, S., and Li, X. (2021). The stress analysis of buried nature gas pipeline in abrupt slopes. In *IOP Conference Series: Earth and Environmental Science*, volume 692/4, page 042086. IOP Publishing.
- [108] Liang, Y., Zheng, J., Wang, B., Zheng, T., and Xu, N. (2020). Optimization design of natural gas pipeline based on a hybrid intelligent algorithm. In *Recent Trends in Intelligent Computing, Communication and Devices, Guangzhou, China*, pages 1015–1025. Springer.
- [109] Liao, Q., Liang, Y., Xu, N., Zhang, H., Wang, J., and Zhou, X. (2018). An milp approach for detailed scheduling of multi-product pipeline in pressure control mode. *Chemical Engineering Research and Design*, 136:620–637.
- [110] Liu, E., Peng, Y., Yi, Y., Lv, L., Qiao, W., and Azimi, M. (2020). Research on the steady-state operation optimization technology of oil pipeline. *Energy science & engineering*, 8(11):4064–4081.
- [111] Liu, E.-B., Peng, Y., Peng, S.-B., Yu, B., and Chen, Q.-K. (2022). Research on low carbon emission optimization operation technology of natural gas pipeline under multi-energy structure. *Petroleum Science*, 19(6):3046–3058. <https://doi.org/10.1016/j.petsci.2022.09.025>.
- [112] Liu, X.-P., Jin, Z.-J., Bai, G.-P., Guan, M., Liu, J., Pan, Q.-H., Li, T., and Xing, Y.-J. (2017). Formation and distribution characteristics of proterozoic–lower paleozoic marine giant oil and gas fields worldwide. *Petroleum Science*, 14(2):237–260. <http://dx.doi.org/10.1007/s12182-017-0154-5>.
- [113] Liu, Y., Chen, S., Guan, B., and Xu, P. (2019). Layout optimization of large-scale oil–gas gathering system based on combined optimization strategy. *Neurocomputing*, 332:159–183.
- [114] Malerba, D., Chen, X., Feng, K., Hubacek, K., and Oswald, Y. (2022). Report no. 11/2022 - the impact of carbon taxation and revenue redistribution on poverty and inequality. Technical report, German Institute of Development and Sustainability (IDOS), Bonn, Germany.
- [115] Manufacturers Standardization Society (2018). MSS-SP-75: Specification for high-test wrought butt welding fittings. Technical report, Manufacturers Standardization Society. <https://msshq.org>.
- [116] Manufacturers Standardization Society (2019). MSS sp-44: Steel pipeline flanges. Technical report, Manufacturers Standardization Society. <https://msshq.org>.
- [117] Marques, J. C. R. et al. (2013). *Robust design of water distribution networks for a proactive risk and uncertainty management*. PhD thesis, Universidade De Coimbra, Department of Civil Engineering.

- [118] Martin, D. (2023). Indian oil market, outlook to 2030. <https://iea.blob.core.windows.net/assets/4a13289b-1e25-45c8-9faf-9db532eaed1c/IndianOilMarket-Outlookto2030.pdf>.
- [119] Menon, E. S. (2004). *Liquid pipeline hydraulics*. CRC press.
- [120] MirHassani, S. and Noori, R. (2011). Implications of capacity expansion under uncertainty in oil industry. *Journal of Petroleum Science and Engineering*, 77(2):194–199. <https://doi.org/10.1016/j.petrol.2011.03.009>.
- [121] MOP (2021). CO2 Baseline Database for the Indian Power Sector. *Central Electricity Authority 2021* (online). https://cea.nic.in/wp-content/uploads/tpe_cc/2022/02/UserGuide_ver172021.pdf.
- [122] MOPNG (2021). Industry Quality Control Manual for Non-Aviation Petroleum Products. *Industry Manual on Acceptance Of Product By Marketing Companies And Related Issues* (online). <https://hpond.hpcl.co.in/hpcloud/PDFS/INDUSTRY>
- [123] MoPNG (2022). Indian petroleum and natural gas statistics 2021-22. <https://mopng.gov.in/files/TableManagements/IPNG-2021-22L.pdf>.
- [124] Morley, M., Atkinson, R., Savić, D., and Walters, G. (2001). Ganet: genetic algorithm platform for pipe network optimisation. *Advances in engineering software*, 32(6):467–475.
- [125] MOSPI (2020). Energy Statistics 2020. https://www.mospi.gov.in/sites/default/files/publication_reports/
- [126] NACE International (2015). NACE standard MR0175/ISO 15156: Petroleum and natural gas industries - materials for use in h₂s-containing environments in oil and gas production. Technical report, NACE International. <https://store.nace.org/>.
- [127] Nandagopal, N. (2012). Pipeline Systems - Designing, Construction, Maintenance and Asset Management. *Pipeline Systems - Designing, Construction, Maintenance and Asset Management* (online). <https://www.eit.edu.au/resources/pipeline-systems-designing-construction-maintenance-and-asset-management/>.
- [128] Nimesh, V., Sharma, D., Reddy, V. M., and Goswami, A. K. (2020). Implication viability assessment of shift to electric vehicles for present power generation scenario of india. *Energy*, 195:116976.
- [129] Oil Industry Safety Directorate (2012). Design, Construction and Inspection requirements for Cross Country Liquid Hydrocarbon Pipelines. *OISD 141* (online). <https://www.oisd.gov.in/oisd-standards-list>.

- [130] Oil Industry Safety Directorate (2017). OISD 118: Fire protection facilities for petroleum refineries and oil/gas processing plants. Technical report, Oil Industry Safety Directorate. <http://www.oisd.gov.in>.
- [131] Oliver, M. E. (2015). Economies of scale and scope in expansion of the u.s. natural gas pipeline network. *Energy Economics*, 52:265–276. <https://doi.org/10.1016/j.eneco.2015.11.004>.
- [132] Osiadacz, A. J. and Isoli, N. (2020). Multi-objective optimization of gas pipeline networks. *Energies*, 13(19):5141.
- [133] Parker, N. (2004). Using natural gas transmission pipeline costs to estimate hydrogen pipeline costs. *UC Davis: Institute of Transportation Studies*.
- [134] Paul, S. (2022). Climate action and indian steel sector: Commitment at cop26 glasgow 2021. *IIM Calcutta*.
- [135] PDIL (2017). Bkpl, terms of reference. <https://environmentclearance.nic.in/writereaddata/Online/TOR>.
- [136] PetroWiki (2015). Authorizing entities to lay, build, operate or expand natural gas pipelines, gsr340(e). https://petrowiki.spe.org/Pipeline_design_considerations_and_standards.
- [137] Pharris, T. and Kolpa, R. (2008). Overview of the design, construction, and operation of interstate liquid petroleum pipelines. Technical report, Argonne National Lab.(ANL), Argonne, IL (United States).
- [138] PNGRB (2008a). Authorizing entities to lay, build, operate or expand natural gas pipelines, gsr340(e). <https://www.pngrb.gov.in/OurRegulation/NGP-GSR340.html>.
- [139] PNGRB (2008b). Authorizing entities to lay, build, operate or expand natural gas pipelines, gsr340(e). <https://www.pngrb.gov.in/OurRegulation/NGP-GSR340.html>.
- [140] PNGRB (2010). Determining capacity of petroleum, petroleum products and natural gas pipeline, gsr476(e). [https://pngrb.gov.in/OurRegulation/pdf/Reference-Regulation/GSR476\(E\).pdf](https://pngrb.gov.in/OurRegulation/pdf/Reference-Regulation/GSR476(E).pdf).
- [141] PNGRB (2015). Procedure for Development of Technical Standards and Specifications including Safety Standards. *PNGRB T4S* (online). <https://www.pngrb.gov.in/OurRegulation/PNGRB>
- [142] PNGRB (2020a). PNGRB Annual Report 2018-19. <https://www.pngrb.gov.in/pdf/annualreports/AR2018-2019.pdf>.

- [143] PNGRB (2020b). PNGRB Petronet Public Notice 2020. <https://www.pngrb.gov.in/pdf/public-notice/Petronet19032020.pdf>.
- [144] Popov, G., Klimenkov, K., and Kostov, B. (2020). Pipelines designing by using hydraulic criteria equations. In *E3S Web of Conferences*, volume 180, page 01007. EDP Sciences.
- [145] PPAC (2020). PPAC Forecast And Analysis 2020. *PPAC Forecast And Analysis 2020* (online). <https://www.ppac.gov.in/content/71ForecastandAnalysis.aspx>.
- [146] PPAC (2021). PPAC Abridged Ready Reckoner 2021. https://ppac.gov.in/uploads/rep_studies/1670410393_202103100530575284162SnapshotofIndia'sOilGasdata.
- [147] PPAC (2022). India's Oil and Gas Ready Reckoner June2022. *PPAC Ready Reckoner June2022* (online). https://ppac.gov.in/uploads/rep_studies/1664173089Ready.
- [148] Qiu, R., Zhang, H., Gao, X., Zhou, X., Guo, Z., Liao, Q., and Liang, Y. (2019). A multi-scenario and multi-objective scheduling optimization model for liquefied light hydrocarbon pipeline system. *Chemical Engineering Research and Design*, 141:566–579.
- [149] Ramos, E. S. and Batista, L. S. (2020). Natural gas pipeline network expansion under load-evolution uncertainty based on multi-criteria analysis. *Applied Soft Computing*, 96:106697.
- [150] Raut, R., Narkhede, B., Gardas, B., and Huynh, L. (2018). An ism approach for the barrier analysis in implementing sustainable practices: the indian oil and gas sector. *Benchmarking: An International Journal*, 25:00–00.
- [151] Ríos-Mercado, R. Z. and Borraz-Sánchez, C. (2015). Optimization problems in natural gas transportation systems: A state-of-the-art review. *Applied Energy*, 147:536–555.
- [152] Ruan, Y., Liu, Q., Zhou, W., Batty, B., Gao, W., Ren, J., and Watanabe, T. (2009). A procedure to design the mainline system in natural gas networks. *Applied Mathematical Modelling*, 33(7):3040–3051.
- [153] Sakr, M. R. and Gooda, E. A. (2018). Economical velocity through pipeline networks “case studies of several different markets”. *Alexandria engineering journal*, 57(4):2999–3007.
- [154] Saługa, P. W., Zamasz, K., Dacko-Pikiewicz, Z., Szczepańska-Woszczyzna, K., and Malec, M. (2021). Risk-adjusted discount rate and its components for onshore wind farms at the feasibility stage. *Energies*, 14(20):6840.
- [155] Sanaye, S. and Mahmoudimehr, J. (2013). Optimal design of a natural gas transmission network layout. *Chemical Engineering Research and Design*, 91(12):2465–2476.

- [156] Sangroula, U., Han, K.-H., Koo, K.-M., Gnawali, K., and Yum, K.-T. (2022). Optimization of water distribution networks using genetic algorithm based SOP-WDN program. *Water*, 14(6):851. <https://doi.org/10.3390/w14060851>.
- [157] Sharma, B. and Khare, S. K. (2023). Liquid pipeline network modeling with performance parameters sensitivity analysis due to its techno-commercial variables. *Journal of Pipeline Science and Engineering*, page 100126.
- [158] Shestakov, R. A. and Vanchugov, I. M. (2022). Influence of multi-product pipeline telescopicity design on the process of mixing during sequential pumping. *Journal of King Saud University-Engineering Sciences*.
- [159] Silva, B. F., de Oliveira, E. V. A., and da Cunha, M. G. (2024). Change of location class in gas pipelines from a regulatory perspective. *Process Safety Progress*, 43(2):313–320. <https://aiiche.onlinelibrary.wiley.com/doi/abs/10.1002/prs.12582>.
- [160] Singh, J. (2015). *Evaluating the economic impacts of pipeline useage on the Indian Oil & Gas Upstream Supply Chain*. The University of Texas at Arlington, Arlington, USA.
- [161] Singh, R. R. and Nain, P. (2012). Optimization of natural gas pipeline design and its total cost using ga. *International Journal of Scientific and Research Publications*, 2(8):1–10.
- [162] Sinha, S. J. (2021). Fast Tracking Freight in India. *Niti Aayog, RMI*. <https://www.niti.gov.in/sites/default/files/2021-06/FreightReportNationalLevel.pdf>.
- [163] Solutions, E. (2020). Pipelinestudio. <https://www.energy-solutions.com/products/es-operational-management-solutions/pipelinestudio/>.
- [164] Tabkhi, F. (2007). *Optimisation de Reseaux de Transport de Gaz*. PhD thesis, De L’Institut National Polytechnique De Toulouse. <http://www.theses.fr/2007INPT024G>.
- [165] Tashbulatov, R., Karimov, R., and Valeev, A. (2023). Decision support system for feasibility study and determination the optimal way to increase the throughput capacity of main oil pipelines. In *2023 International Russian Smart Industry Conference (SmartIndustryCon)*, pages 269–274. IEEE. <https://doi.org/10.1109/smartindustrycon57312.2023.10110838>.
- [166] Tian, Q., Zhao, D., Li, Z., and Zhu, Q. (2018). A two-step co-evolutionary particle swarm optimization approach for co2 pipeline design with multiple uncertainties. *Carbon Management*, 9(4):333–346.
- [167] Tiewsoh, L., Sivek, M., and Jirásek, J. (2017). Traditional energy resources in india (coal, crude oil, natural gas): A review. *Energy Sources, Part B: Economics, Planning, and Policy*, 12:110–118.

- [168] Tong, L., Han, G., and Qiao, J. (2011). Design of water distribution network via ant colony optimization. In *2011 2nd International Conference on Intelligent Control and Information Processing*, volume 1, pages 366–370. IEEE.
- [169] Tu, R., Jiao, Y., Qiu, R., Liao, Q., Xu, N., Du, J., and Liang, Y. (2023). Energy saving and consumption reduction in the transportation of petroleum products: A pipeline pricing optimization perspective. *Applied Energy*, 342:121135. <https://doi.org/10.1016/j.apenergy.2023.121135>.
- [170] Uster, H. and Dilaveroglu, S. (2014). Optimization for design and operation of natural gas transmission networks. *Applied Energy*, 133:56–69.
- [171] Uyanik, M. C. and Bozkucs, Z. (2024). Introducing a newly developed computer software to analyze fluid transients in pressurized pipeline systems. *Arab. Journal of Sci. Eng.*
- [172] Van Vuuren, S. (2002). Application of genetic algorithms-determination of the optimal pipe diameters. *Water SA*, 28(2):217–226.
- [173] Vertommen, I., van Laarhoven, K., and Cunha, M. d. C. (2021). Robust design of a real-life water distribution network under different demand scenarios. *Water*, 13(6):753.
- [174] Virtanen, P. e. a. and SciPy 1.0 Contributors (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. *Nature Methods*, 17:261–272.
- [175] Wang, B., Liang, Y., Zhao, W., Shen, Y., Yuan, M., Li, Z., and Guo, J. (2021). A continuous pump location optimization method for water pipe network design. *Water Resources Management*, 35(2):447–464.
- [176] Wang, B., Yuan, M., Yan, Y., Yang, K., Zhang, H., and Liang, Y. (2019). Optimal design of an oil pipeline with a large-slope section. *Engineering optimization*, 51(9):1480–1494.
- [177] Wang, B., Yuan, M., Zhang, H., Zhao, W., and Liang, Y. (2018). An milp model for optimal design of multi-period natural gas transmission network. *Chemical Engineering Research and Design*, 129:122–131.
- [178] Wang, C.-N., Nhieu, N.-L., Tran, K.-P., and Wang, Y.-H. (2022). Sustainable integrated fuzzy optimization for multimodal petroleum supply chain design with pipeline system: The case study of vietnam. *Axioms*, 11(2):60.
- [179] Wang, G., Zhao, W., Qiu, R., Liao, Q., Lin, Z., Wang, C., and Zhang, H. (2023). Operational optimization of large-scale thermal constrained natural gas pipeline networks: A novel iterative decomposition approach. *Energy*, 282:128856. <http://dx.doi.org/10.1016/j.energy.2023.128856>.

-
- [180] Wang, Z., Cardenas, G., Weihs, G. F., and Wiley, D. (2013). Optimal pipeline design with increasing co2 flow rates. *Energy Procedia*, 37:3089–3096.
- [181] Xu, S., Wang, J., Sun, H., Huang, L., Xu, N., and Liang, Y. (2022). Life cycle assessment of carbon emission from natural gas pipelines. *Chemical Engineering Research and Design*, 185:267–280. <https://doi.org/10.1016/j.cherd.2022.07.018>.
- [182] Yu, H. and Guo, M. (2012). An efficient oil and gas pipeline monitoring systems based on wireless sensor networks. In *2012 International Conference on Information Security and Intelligent Control*. IEEE.
- [183] Zarei, J. and Amin-Naseri, M. R. (2019). An integrated optimization model for natural gas supply chain. *Energy*, 185:1114–1130.
- [184] Zhou, J., Peng, J., Liang, G., Chen, C., Zhou, X., and Qin, Y. (2021). Technical and economic optimization of natural gas transmission network operation to balance node delivery flow rate and operation cost. *Journal of Intelligent & Fuzzy Systems*, 40(3):4345–4366.
- [185] Zhou, J., Zhao, Y., Fu, T., Zhou, X., and Liang, G. (2022). Dimension optimization for underground natural gas storage pipeline network coupling injection and production conditions. *Energy*, 256:124651.
- [186] Zhou, X., Zhang, H., Xin, S., Yan, Y., Long, Y., Yuan, M., and Liang, Y. (2020). Future scenario of china’s downstream oil supply chain: Low carbon-oriented optimization for the design of planned multi-product pipelines. *Journal of Cleaner Production*, 244:118866.

Appendix A

PROGRAMMING LANGUAGE

Python Programming Language is employed for modelling and optimizing pipeline networks, leveraging the powerful capabilities it offers in data analysis and scientific computing. This task is facilitated through the use of Jupyter Notebook, a versatile platform that enhances the interactive exploration and documentation of the optimization process. The computational tasks are executed on a standard personal computer equipped with an Intel Core i5 processor, 11th Generation, running at 2.4GHz with a 64-bit architecture. With 8GB of RAM, this setup provides sufficient computational power and memory capacity to handle the modelling and optimization tasks efficiently.

ADVANTAGES

Python is preferred over other programming languages, including MATLAB, for several reasons:

1. **Adaptability:** Python is a versatile programming language, capable of utilization across various domains such as automation, web development, data analysis, scientific computing, artificial intelligence, machine learning, and beyond. In contrast, MATLAB is predominantly oriented towards engineering applications and numerical computing.
2. **Open Source Nature:** Python operates under an open-source model, enabling users to utilize, distribute, and modify it freely. This facilitates a robust and expansive developers community who actively contribute to its enhancement and evolution. MATLAB, on the other hand, is proprietary software, necessitating a license for commercial utilization.
3. **Wide Array of Libraries:** Python offers an extensive array of libraries and frameworks that cater to a wide range of tasks and domains. For example, NumPy, SciPy, Pandas, Matplotlib, and Scikit-learn are widely used for scientific computing and data analysis.

TensorFlow and PyTorch are popular for machine learning and deep learning. This rich collection of libraries makes Python a powerful tool for developers, researchers, and engineers. While MATLAB also has a rich set of toolboxes, Python's libraries often provide similar functionality and are more accessible due to Python's open-source nature.

4. **Community Support:** Python benefits from a large and vibrant community of developers, researchers, and enthusiasts who contribute to its ecosystem through forums, documentation, tutorials, and open-source projects. This community support fosters learning, collaboration, and innovation. MATLAB also has a community, but it's generally smaller and more focused on specific domains.

Overall, Python's versatility, open-source nature, extensive libraries, active community, ease of learning, and integration capabilities make it a preferred choice over MATLAB and other programming languages for many developers and researchers. However, the suitability of a programming language ultimately depends on the specific requirements and constraints of each project.

LIBRARIES

The programmed code utilized various Python libraries used for modelling and optimizing pipeline networks. Below is a breakdown of the libraries and their functionalities:

1. **colebrook:** This library offers functions related to the Colebrook-White equation, which is commonly used for calculating the friction factor in fluid flow.
2. **numpy_financial:** This library provides financial functions for various calculations such as present value, future value, net present value, etc.
3. **opytimizer:** This library offers optimization algorithms and tools for solving optimization problems. It includes various optimizers and components like search spaces and functions.
4. **pymoo:** This library is used for multi-objective optimization and includes algorithms such as NSGA, as well as tools for defining problems, operators, and termination criteria.

Additionally, the code imports several standard Python libraries and tools:

- **os:** Operating system interface for interacting with the underlying operating system.
- **copy:** Provides functions for shallow and deep copying of objects.

- **time**: Time-related functions for measuring execution time or delaying execution.
- **sys**: System-specific parameters and functions, used for handling Python runtime environment.
- **numpy**: Fundamental package for scientific computing with Python, used for array operations and mathematical functions.
- **matplotlib**: A plotting library for creating visualizations in Python.
- **datetime**: Provides classes for manipulating dates and times.
- **bisect**: Provides binary search functionality.

These libraries collectively provide the necessary tools and functionalities for modelling, optimization, and analysis tasks related to pipeline networks.

PREDEFINED PARAMETERS

Various pre-defined parameters are used in the modelling and optimization of pipeline networks, which are mentioned below.

1. Hydraulic Parameters:

- Operational days and hours.
- Roughness of the pipeline.
- Densities of steel pipe and coating.
- Corrosion allowance and coating thickness.
- Minimum back pressure and maximum pressure and yield strength.
- Critical Reynolds number.

2. Cost Parameters:

- Tax rate.
- Costs related to various components such as basket filters, sump tanks, pumps, etc.
- Cost of FPS at different locations.
- Tankage cost.
- Laying costs, including land cost and annual royalty cost.
- Cost of steel and coating.

- Survey, field engineering, cathodic protection, and telecom costs.
- Linefill product cost, electricity cost, and manpower cost.
- Various Operation and Maintenance (OM) factors.

3. **Tariff Calculations Parameters:**

- Depreciation rates of telecom, mechanical, tank, pipeline, and electrical components.
- Income tax return.

4. **Carbon Emission Factors:**

- Carbon footprint parameters including steel and electricity CO2 emissions.
- Coating carbon emission.
- Carbon emissions from pipe installation.

These parameters play crucial roles in the modelling, optimization, and cost analysis of pipeline networks. They represent various aspects such as hydraulic properties, material characteristics, financial considerations, and environmental impacts. Adjusting these parameters allows for fine-tuning the model and optimizing the design and operation of pipeline networks.

USER INPUTS

Various user input parameters are considered in the analysis, which is mentioned below.

- **Analysis Period:** The period over which the analysis is conducted.
- **Length, Volume, and Design Factor:** Length of pipeline sections, MS and HSD volumes, and design factor for each section.
- **Ambient Temperature and Reference Density:** Ambient temperature and reference density are used in calculations.
- **Elevation Loss and Slope:** Elevation loss and slope between pipeline sections.
- **Rate of Change:** Factors for rate of change of various costs including OPEX, CPI, Discount factor and Tariff.
- **IRR:** Target internal rate of return for the project.

These parameters are essential for conducting the analysis and determining the feasibility and performance of the pipeline project.

SUBMODULES

Various sub-modules which used are mentioned below

- **Conversion into Sub-Nodes:** This part of the code converts the main program (without intermediate nodes) into sub-nodes. It iterates over the length of pipeline sections, calculates the number of sub-nodes, and initializes arrays for various parameters such as length, volume, design factor, ambient temperature, etc.
- **Volume, Outer Diameter (OD) Boundary, Kinematic Viscosity, and Density:** This section computes the total volumes of MS and HSD over the analysis period, section-wise kinematic viscosity, and density. It also calculates the lower bound of outer diameter (OD) based on velocity and defines a range of ODs for each section.
- **Kinematic Viscosity & Density Evaluation:** This function computes the kinematic viscosity for MS, HSD, and SKO based on the ambient temperature. Given the ambient temperature and reference temperature, this function computes the density for MS, HSD, and SKO.
- **Closest Function for OD & Thickness:** It returns the closest value of Pipeline Diameter and Thickness in an API 5L list to a given number.

These sub-modules are essential for the proper functioning of the pipeline network optimization program and aid in the computation of various parameters required for analysis.

Appendix B

PROBLEM STATEMENT INPUTS

- **Analysis Period:** 25 years
- **Ambient Temperature:** $22.53^{\circ}C$ & $30^{\circ}C$ for CMPL & CIPL respectively
- **Escalation Factors:** OPEX, CPI, Discount factor, Tariff & IRR: 3%, 2%, 1%, 1% & 12% respectively
- **Section Length, Volume, Design Factor, and Elevation Loss:**

Parameter	CMPL	CIPL
Section Length (in Km)	[130.4, 139.5, 56.9, 38.7, 162, 134, 92,83]	[25.93, 19.47, 65.24, 39.14, 28.80, 43.23, 1.70, 38.10, 31.55, 2.61, 38.84, 21.36]
MS Volume (in MT)	[365700, 548500, 438800, 377800, 0, 219400, 178000, 669700]	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 602000]
HSD Volume (in MT)	[585100, 243800, 219400, 536300, 195000, 219400, 121900, 681300]	[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1440000]
Design Factor	[0.605, 0.495, 0.440, 0.440, 0.72, 0.72, 0.672, 0.672]	[0.6535, 0.6535, 0.6535, 0.6535, 0.6535, 0.6535, 0.6535, 0.6535, 0.6535, 0.6535, 0.6535, 0.6535]
Elevation Loss (in m)	[0, 0, 0, 0, 0, 0, 0, 0]	[14.8, -34.80, -33.40, -117, -48.9, -38, -21.8, 7.4, -13.7, -3.4, 5.9, -0.5]

Appendix C

LIST OF PUBLICATIONS

Publications from Thesis

1. Paper 1 *Sharma, B., & Khare, S. K. (2023). Liquid pipeline network modeling with performance parameters sensitivity analysis due to its techno-commercial variables. Journal of Pipeline Science and Engineering, 3(3), 100126;*
<https://doi.org/10.1016/j.jpse.2023.100126>.
2. Paper 2. *Sharma, B., & Khare, S. K. (2024). Optimizing multi-product pipeline network configuration design: A comprehensive framework with objective function sensitivity analysis. IEEE Access: Practical Innovations, Open Solutions, 12, 18804–18820.*
<https://doi.org/10.1109/access.2024.3360193>.

Appendix D

PLAGIARISM REPORT

xyz			
ORIGINALITY REPORT			
5%	4%	%	3%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS
PRIMARY SOURCES			
1	archive.org Internet Source		1%
2	Submitted to University of Petroleum and Energy Studies Student Paper		1%
3	idoc.pub Internet Source		1%
4	Submitted to National University of Singapore Student Paper		<1%
5	Submitted to University of Bath Student Paper		<1%
6	Submitted to King Fahd University for Petroleum and Minerals Student Paper		<1%
7	www.pngrb.gov.in Internet Source		<1%
8	Submitted to University of Stellenbosch, South Africa Student Paper		<1%