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RESEARCH ARTICLE

Optimizing Multi-Product Pipeline Network Configuration Design: A Comprehensive Framework With Object Function Sensitivity Analysis

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ABSTRACT This work presents a novel framework for the design optimization of Pipeline Network Configuration which takes into account the intricate relationships among decision variables and the essential technical, commercial, and environmental design parameters. To illustrate the Single Horizon Optimization methodology's efficacy and sensitivity analysis of different objective functions, a case study of the China Multi-product Pipeline is utilized. It is found that each performance parameter excels in its respective objective function, however, a novel Tariff & Carbon-Emissions Multi-Objective Function stands out by delivering a well-balanced outcome, reducing overall cost, tariff, and carbon emissions by -1.98%, -1.76%, and -3.48%, respectively. The article also delves into various Multi-Horizon Optimization (MHO) methodologies aligning with practical industry practices, and the case study of the Central India Pipeline is used. The Pumping-Station MHO shows a potential cost savings of 1.21 Billion INR to the pipeline owner, along with a reduction of tariffs by 139 INR/MT across the analysis period. The Pipeline-Laying MHO analysis reveals that the initial phasing for the PNC design shall be up to the year when demand reaches 80% of the total demand. The proposed framework empowers designers with better decision-making capabilities for economically viable and environmentally sustainable pipeline network design.

INDEX TERMS Energy, multi-horizon optimization, multi-objective function, NSGA-II, petroleum, pipeline network design, tariff, technical-commercial-environmental.

I. INTRODUCTION

The petroleum industry has been facing a significant challenge in recent years driven by a range of factors, including increased demand, supply chain disruptions due to the Russia-Ukraine War, geopolitical tensions in the Middle East, natural disasters like COVID-19, and fluctuation of petroleum product prices [1].

Overall, the issue of rising petroleum product prices is a complex and multifaceted challenge, and unburdening the supply chain is one of the crucial areas that recently enticed the attention of the government and other stakeholders. This includes investing in pipeline transportation, which is a safe, economical, quick, and energy-efficient option, ensuring a stable, secure, and sustainable supply of large quantities of petroleum products over long distances [2], [3], [4], [5], [6]. Many countries, including India and China, are investing heavily in the construction of extensive pipeline networks to address this problem [7]. However, it is important to note that constructing a pipeline network is a capital-intensive project that has a lasting impact on the entire supply chain. Therefore, the optimization of Pipeline Network Configuration (PNC) design is an inevitable necessity. The optimization of PNC design involves three major components: Decision Variables, Objective Function, and Optimization Methodology. The Decision Variables must include the number & location of

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pumping stations and the pipeline's internal diameter, as all other variables are implicitly or explicitly dependent on them. These decision variables are in trade-off with each other. Many previous works had considered them holistically [5], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41]. However, they have not considered the complete set of commercially available diameters and thicknesses of pipelines. While it is a general industry practice, to the best of our knowledge, none of the previous works have thoroughly explored the repercussions of introducing other intermediate nodes such as Sectionalizing Valve (*SV*) stations and Intermediate Pigging Stations (*IPS*) within the context of PNC design optimization. These intermediate nodes have the potential to serve as viable locations for constructing intermediate pumping stations, offering an alternative to solely relying on intermediate receiving stations. This oversight represents an untapped opportunity to broaden the solution space, providing optimizers with the potential to uncover more effective and optimal solutions.

In the classical optimization problems, emphasis was given to commercial performance parameters such as pipeline Capital Expenditure (CAPEX), Operational Expenditures (OPEX), and/or both as Overall Cost (OC) projected as either mono-objective functions [5], [6], [9], [11], [14], [17], [18], [20], [21], [22], [23], [24], [33], [34], [39], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54] or multi-objective functions [3], [8], [13], [29], [32], [36], [37], [41], [55], [56], catering the concerns of the pipeline owners. References [6], [10], and [57] had opined the tariff performance parameter which will provide a balanced approach for evaluating the overall commercial aspect of the pipeline project and also ensure a fair tariff price for pipeline users. With a growing worldwide consensus on the imperative to address carbon emissions as part of the broader effort to combat climate change and transition towards sustainable solutions that benefit all stakeholders [58]. A detailed literature review of carbon emissions from the overall oil and gas network was discussed by [59] and [60]. Many authors [6], [8], [16], [40], [41], [56], [56], [61] had considered carbon emission from PNC design and its operations as a performance parameter in the neoclassical optimization approach. Recently, [62] suggested dynamic carbon emission factors, as mentioned in the equation (11), as shown at the bottom of page 5, which will impact the objective function during multi-horizon PNC design optimization. It is crucial to highlight that carbon emissions and tariffs, not only have notable distinct exclusive impacts, but they also exhibit significant variations in the range of their outcome values. It was found that none of the previous authors had contemplated the integration of a multi-objective function that simultaneously assesses the tariff and carbon-emission performance parameters. This multifaceted evaluation is indispensable, as it ensures that the pipeline project is not only commercially viable but also environmentally sustainable and socially responsible, leading to long-term benefits for all stakeholders involved.

Over the years, pipeline owners and designers have developed practical techniques for pipeline network design. Traditionally, pipeline engineers have relied on their experience and judgment, often employing a trial-and-error approach. This method takes into account numerous factors, including route and terrain conditions, pipeline volume and buildup, environmental considerations, technical constraints, and economic factors. However, with an increase in the number of sections and variables, the complexity of finding a solution also increases. This has made the process iterative, intricate, time-consuming, and prone to suboptimal outcomes [10], [26], [42]. Therefore, it is crucial to ensure that the pipeline network is designed and supported by appropriate scientific methods. To address this challenge, a variety of system-based optimization methodologies have been introduced in the literature. They reduce costs, enhance efficiency, and improve the overall quality and reliability of the design process. By concurrently considering all pertinent variables, these methodologies reduce the computation time of PNC design optimization from several days or hours to a few minutes, enabling designers to explore a wider range of solutions and reduce investment [26], [49], [63]. These methodologies consist of optimizers for identifying the most optimal PNC to achieve the most optimum state for a particular problem statement while satisfying hydraulics and objective function requirements. It will ensure that pipeline owners can make informed investment decisions and operate their pipeline network with greater efficiency & effectiveness.

The variation in the demand volume of markets attached to the pipeline network is inevitable and perquisite to the PNC design and operations optimization [3], [10], [23], [37], [57]. This optimization is dealt with in multi-horizon optimization methodology in which Technical Environmental Commercial (*TEC*) factors will be inconstant such as dynamic pump efficiency factor, the inflation rate in operations and construction cost, and rate of change in carbon emission factors [62]. Further, demand variation needs to be dealt with according to its nature of manifestation which is uncertain demand variations and estimated demand variations. Reference [25] had reviewed and presented different types of approaches available to deal with demand uncertainty during PNC design optimization. The author had considered the scenario-based robust optimization approaches, however assigning the probability to each possible scenario is difficult, and subjective and may lead to erroneous results. Reference [13] had suggested design provisions to handle volume uncertainty such as the selection of higher diameters, and margins in operating pressure design pressure. They suggested a direct trade-off in pipeline robustness to handle uncertainty in demand volume and its total cost. Reference [43] found that for uncertain volumes that involve temporary surges in demand and have a lower impact on the overall market demand, it is better to consider these margin provisions rather than phasing the PNC such as the construction of additional pumping stations. Reference [51] had suggested the construction of additional storage capacity of tanks to handle contingency sales during its initial phase of construction. These design margins are compiled and considered in the PNC model provided by [62] that is considered in this study. Reference [50] suggested consideration of external provision of dosing anti-turbulence additives for additional pipeline capacity margin. For the estimated demand, on the other side, [16] suggested that the optimization shall not be solely dependent upon design margin provisions, otherwise, it will lead to pipeline overdesign, especially for long-distance pipelines with large differences in the flow rate due to demand variations. Hence, it is essential to consider both design margins and phasing of PNC to handle minor demand uncertainty which ensures better financial viability and reliability together. Many authors [14], [45], [48] studied the impact of estimated volume variation on a selection of pipeline diameter and its thickness during its design. References [16], [64], and [50] suggested phasing of laying parallel pipelines across the initial phase mainline during the time horizon. Similarly, [28] had studied pipeline network extension to more demand nodes in a phased manner. References [11], [33], and [65] had proposed phasing of the pipeline project across a multi-horizon period by considering both - laying a new pipeline and constructing a new pumping station. However, the authors had not considered other intermediate stations as potential nodes for pumping stations, impacting the overall optimization. This article illustrates the multi-phase optimization methodologies to handle estimated demand variation based on the actual industry practices applied for the pipeline project phasing.

It is vital to emphasize that the intent of the proposed work is not to supplant the expertise of designers but, rather, the main thrust is to develop a systematic decision-supporting tool to augment the design engineers, pipeline owners, and regulatory bodies' decision-making capabilities, to deliver more streamlined, efficient, and effective solutions for PNC design optimization. Moreover, the proposed framework can be adapted for other applications like electric, roads, and water network design [11].

The subsequent sections of this article are meticulously organized as follows. Section II provides a detailed insight into the novel PNC design optimization framework, elaborating on its key components, including PNC mathematical modeling, different types of objective functions, and optimization methods. Section III introduces an innovative nested-optimizer approach for Single-Horizon Optimization (*SHO*), which forms the foundation for the subsequent Multi-Horizon Optimization (*MHO*) methodologies. Section IV is dedicated to exploring multiple *MHO* techniques designed to address PNC design challenges in the context of demand variations. Further, Section V presents the practical results of the proposed *SHO* & *MHO* optimization methodologies using case studies. This section offers an extensive evaluation and discussion of the influence exerted by different mono and multi-objective functions on the *SHO* results. Ultimately, this section investigates the ramifications of various *MHO* methodologies on multi-horizon problem statements, providing a holistic understanding of their impact. In a culminating Section VI, the research findings of the PNC design optimization are consolidated, offering a comprehensive summary of the outcomes and concluding insights for the research.

II. PNC DESIGN OPTIMIZATION FRAMEWORK

A typical PNC design optimization framework comprises two fundamental components: the hydraulic assessment and the objective function analysis. In the hydraulic segment, the evaluation focuses on hydraulic parameters, ensuring that the pipeline network adheres to technical feasibility by scrutinizing boundary constraints. In the subsequent objective function phase, the appropriate methodology is formulated to explore the solution space of the decision variables and determine the combination of variables that leads to the most optimal PNC design based on the best value(s) of the performance parameter(s) in the objective function.

Mathematical modeling is the foremost step for the design and optimization of the PNC. To derive a mathematical model for PNC optimization, consider the PNC depicted in Figure 1, consisting of the "n" number of the nodes.

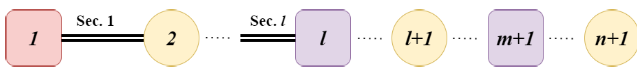

FIGURE 1. General pipeline network configuration.

The total pressure required at an intermediate node "k" to overcome frictional drag, elevation differences, and maintain minimum back-pressure up to node "m" is calculated using equation (1), which is derived from fluid mechanics principles and is commonly used in pipeline design [28], [66]. For nodes other than pumping stations, any pressure loss upstream of these nodes is taken care of by the preceding pumping station. In the absence of pumping facilities, any pressure loss in the upstream sections of such nodes will be compensated by their respective prior pumping station.

$$P_{D_l} = P_{B_m} + \sum_{i=l}^{m-1} (P_{E_i} + P_{F_i} + P_{M_i}) \tag{1}$$

The elevation pressure P_{E_i}, is required to handle elevation differences between the section nodes. Frictional or head loss P_{F_i}, is required to overcome pipe wall resistance for the given demand volume V_i and stated in equation (2). P_{M_i} and P_{B_m}, are required to manage the minor losses and minimum back-pressure respectively.

$$P_{F_i} = \frac{f_i \times V_i^2 \times \rho}{12.1 \times D_i^5 \times L_i \times T_O^2} \tag{2}$$

Hence, PNC needed to derive from optimization tool such that pressure at PNC nodes satisfies the equation (1) within the boundary limits mentioned in the equation (3) below.

$$P_B \leqslant P_l \leqslant P_I \tag{3}$$

Further, the technical feasibility of the PNC, is dependent upon the compliance of the boundary conditions for thickness, and velocity, as described in equations (4), and (5) respectively.

$$t_l \geqslant \begin{cases} 5.56mm \\ 0.01 \times OD_l \end{cases} \tag{4}$$

$$v_E \leqslant v_l \leqslant v_U \tag{5}$$

It is important to note that these boundary conditions must be satisfied simultaneously, and any violation of these conditions can result in pipeline failure, causing severe consequences such as environmental damage, loss of life, and economic loss.

As discussed in the literature review, the proposed framework enhances PNC design optimization by significantly broadening the range of decision variables. This expansion inherently amplifies the search space for the optimizer, augmenting the potential for uncovering superior solutions. The proposed framework takes into account all commercially available pipeline diameters and thicknesses in accordance with API 5L standards. Additionally, an innovative method has been introduced, which leverages the problem statement's demand characteristics and velocity constraints specified in equation (5). This method facilitates the selection of a set of techno-commercially viable diameters for the l^{th} section during the optimization process, as described in equation (6), ensures the optimization process remains efficient, effective, and expeditious.

$$\sqrt{\frac{1.273 \times Q_l}{v_U}} \leqslant D_l \leqslant \sqrt{\frac{1.273 \times Q_l}{v_E}} \tag{6}$$

Furthermore, this framework extends its consideration to the potential utilization of intermediate stations, specifically *SV* and *IPS*, as potential nodes for the construction of intermediate pumping stations. This provision comes with the condition that the pipeline diameter in sections after the *SV* station node will not change with respect to their predecessor section, due to the limited process facility. On the other side, when the *SV* station is converted to an intermediate pumping station node during optimization, the set of applicable decision variables for the pipeline diameter will be varied resulting in the direct complex relation of diameter decision variable on another decision variable that is location and number of the intermediate pumping station selected by its optimizer. Therefore, these interdependent variables need to be dealt with exclusively by individual nested optimizers through system-based optimization methodologies, discussed in subsequent sections of this article.

For the same problem statement, multiple feasible PNCs are possible and hence design decision on selection is based on the objective function. In a linear algebraic problem, it is possible to derive a perfectly designed pipeline network by taking the derivative of its combined mathematical function with respect to the variable, making the resultant equation equal to zero, and then finding a solution for the given variable [67]. But in a real scenario, it is a complex non-linear problem that involves boundary conditions, and most importantly multiple conflicting variables. Each variable influences performance parameters to some extent while ensuring the technical feasibility of the PNC and hence the task of establishing the optimum is tedious. The objective function is a mathematical expression based on a set of exclusive performance parameters which are a function of the decision variables augmented with hard-penalty functions ensuring both technical feasibility and commercial viability of the PNC solution, mathematically represented in equation (7).

$$\begin{aligned} &Min \sum_{q=1}^{v} PP_q(x) \\ &s.t., HC(x) = 0 \end{aligned} \tag{7}$$

where $PP_1(x), PP_2(x), \ldots, PP_v(x)$ represent the multiple objectives to be optimized. If any of the objectives are to be maximized, they can be converted to minimization problems by taking their inverse. The mathematical expression of OPEX, CAPEX, tariff, and carbon emissions performance parameters is mentioned in the equations (8), (9), (10) and (11) respectively [62]. The *HC(x)* is a hard constraint imposed on the non-compliance of these critical boundary conditions mentioned in the equations (3), (4), and (5).

$$\begin{aligned} OPEX &= \sum_{t=1}^{N} \frac{OPEX_t}{(1+df)^{t-1}} \\ &\quad \text{s.t. } OPEX_t = 0 \text{ for } PH_t \neq 0 \\ &\quad \text{and till pipeline commissioned, where} \\ OPEX_t &= \Big(O_E + O_L + O_M + (C_{OM-S} \times O_S) \\ &\quad + C_{OM-P} \times \big(C_{PC} \times \rho_s \times S_P \times (1 + C_{TNC})\big) \\ &\quad + \sum_{i=1}^{n} C_{OCP} \times L_i + C_{IN} \times (O_P + O_S - O_L)\Big) \\ &\quad \times (1 + op_E)^{t-1} \end{aligned} \tag{8}$$

$$\begin{aligned} CAPEX &= \sum_{t=1}^{N} \frac{CAPEX_t}{(1+df)^{t-1}} \text{where,} \\ CAPEX_t &= PH_t \times \Big((O_P + O_S) \times (1 + C_{SP} + C_{EP} + C_{EN}) \\ &\quad \times (1 + C_{SO} + C_C + C_{SO} \times C_C) + C_{LF} \\ &\quad \times \sum_{i=1}^{n} L_i \times A_i\Big) \times (1 + cpi)^{t-1} \end{aligned} \tag{9}$$

$$T = \frac{\sum_{t=1}^{N} \frac{CAPEX_t + OPEX_t + IT_t}{(1+irr)^{t-1}}}{\sum_{t=1}^{N} \frac{(V \times ((1+ta_E) \times (1+t_v))^{t-1})}{(1+irr)^{t-1}}} \tag{10}$$

A comparative analysis of design alternatives based on the change in the number and placement of pumping stations is straightforward, while the same is not true for pipeline diameter decision variables, especially for large networks. Therefore, the concept of Pipeline Length-Weighted Diameter (PLWD) is proposed which will indicate a change in pipeline diameters across the pipeline length as mentioned in equation (12). It's important to note that the PLWD does not correspond to precisely represent the diameter of either pipeline section. Rather, it represents the average diameter, providing a useful metric for assessing the post-optimization overall change in diameter across the large pipeline network.

$$PLWD = \frac{\sum_{i=1}^{n} L_i \times D_i}{L} \tag{12}$$

Using the ratio of pipeline capacity to total length as a measure for evaluating average diameter is inaccurate because pipeline capacity is not solely determined by the average diameter; it is also influenced by the number of pumping stations. Consequently, pipelines with the same average diameter can have different capacities due to variations in the number of pumping stations.

The primary aim of PNC design optimization is to find the most optimal values of the decision variables that either maximize or minimize the objective function, while also meeting a set of constraints. The accuracy of selecting the optimal network configuration is ensured by relying on an extensive database of the most recent feasibility reports and published information. However, the objective of this work is not to establish the exact cost of each component but to provide reasonable estimates of all crucial components that are typically considered in practical *TEC* analysis of pipeline design. The selection of optimizer varies according to objective functions such as Ant colony optimization (ACO), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Artificial Immune System (AIS), Generalized Reduced Gradient (GRG), or Simulated Annealing (SA) for the mono-objective or multi-to-mono objective function, and ϵ-constraint method, Boolean Particle Swarm Optimization (BPSO), or Non-Dominated Sorting Genetic (NSGA) for the multi-objective function. The proposed models are not meant to replace or undermine the effectiveness of these established methods, but it is intended to demonstrate that such complex laborious evaluation of multiple processes can be accelerated and design procedure can be standardization can be ensured by system-based assessment. The proposed framework takes a fraction of a second on a Core-i5 processor, compared with the manual procedure by an average design engineer will take not less than 5 minutes on each configuration and 5 hours on further cost and emission analysis for each feasible solution. Based on the time horizon of the problem statement, there are two types of optimization methodology - Single Horizon Optimization (*SHO*) Methodology and Multi Horizon Optimization (*MHO*) Methodology. The GA, BPSO, and NSGA optimization algorithms are considered in this work for mono-objective functions and multi-objective functions. Further, this study intends to present a holistic framework for PNC design optimization, rather than to compare the performance of different optimizers. The impact of other optimizers on the outcome will be analyzed in future studies.

III. SINGLE HORIZON OPTIMIZATION METHODOLOGY

The optimization methodology aims to develop a systematic programming algorithm that can provide an optimal PNC design solution while considering the technical, commercial, and environmental parameters in the problem statement. A Single Horizon Optimization Methodology is opined for the problem statement which has considered the constant demand volume across the time horizon and hence, there is no capacity expansion or PNC extension. The proposed nested optimizer framework deals with interdependent binary and discrete decision variables under the influence of non-linear boundary conditions and penalty functions. Figure 2 illustrates the flowchart of the proposed *SHO* methodology, and the steps involved are described briefly below:

$$\begin{aligned} CE = \sum_{t=1}^{N} \Bigg(& \big(C_{SCE} \times {\gamma_{SCE}}^{t-1} + C_{RD} \times (L_{MP} + 0.5 \\ & \times \sum_{i=1}^{n} L_i)\big) \times (S_{P_t} + S_{T_t}) + \sum_{i=1}^{n} \big(B_{PS_i} \times C_{ECE} \times T_O \\ & \times P_{KW_{i_t}} \times {\gamma_{ECE}}^{t-1} + (B_{IPPS_i} \times (C_{N-PS} + N \\ & \times C_{AX}) + B_{IPRS_i} \times C_{E-PS}\big) + C_{SE} \times \sum_{i=1}^{n} L_i \times (D_i \\ & + w_C)^2 + C_{FG} \times V \times (1 + t_v)^{t-1} + C_{SX} \times \sum_{i=1}^{n} \\ & \frac{(L_i \times (D_i + w_C + b_T) \times h_{T_i})}{(141.5 \times Ex_B + 10.23 \times Ex_C + 290.73 \times Ex_E - 0.521 \times Ex_{HP} + C_{SOC})} \Bigg) \end{aligned} \tag{11}$$

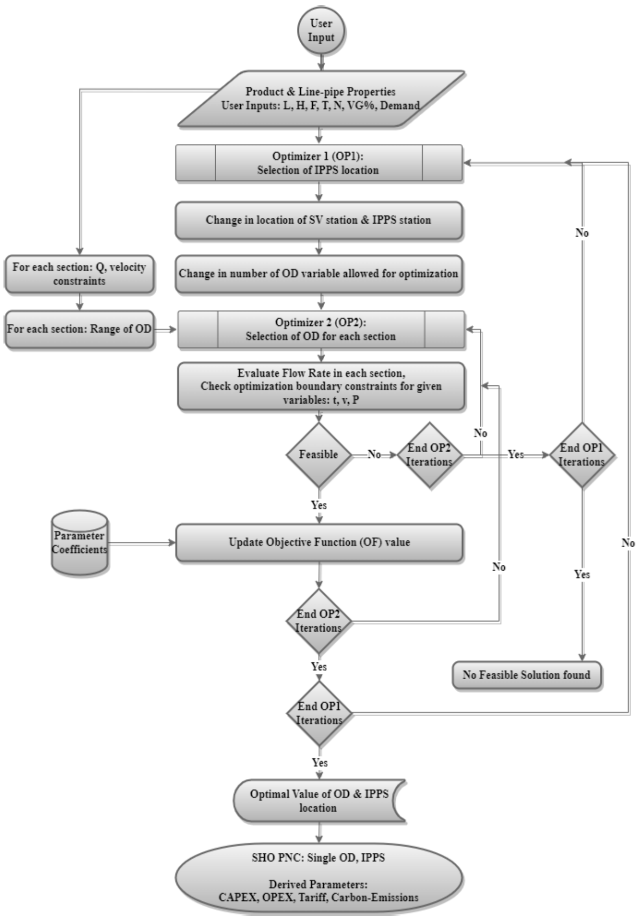

FIGURE 2. Single horizon optimization methodology.

1) **Initialization of Decision Variables:** The initialization involves fetching technical, environmental & commercial inputs from the problem statement and creation of sub-nodes. The technical inputs are the number of receiving stations & their chainage distance, the average design factor of each section, elevation profile, product-wise demand volume, an ambient temperature of each section, volume escalation & material, and grade of line pipe; commercial inputs are analysis period, operational cost escalation, tariff escalation, and desired IRR; and environmental inputs are carbon emission variation rate for steel & electricity. Subsequently, based on the ambient temperature of the pipeline and the product type, the product density and viscosity are updated. Then, the sub-algorithm is developed which will create an intermediate-nodes station depending upon the station inter-distances and terrain information such as pipeline elevation. During the outer loop, an initial population of intermediate pumping stations across the nodes is allocated by the first optimizer (*OP1*), and based on the location of an intermediate pumping station, the position of *IPS* and *SV* stations is updated. Further, based on the position of the *SV* stations, sections where a variation of pipeline diameters allowed with respect to their precedent sections are decided. The nested second optimizer (*OP2*) selects the range of pipeline diameters from all available commercial diameters for each section based on the velocity boundary which is located inside the *OP1* objective function. Based on Barlow's formula, corresponding pipeline thickness is selected from all available commercial thicknesses of the associated diameter.
2) **Objective Function Evaluation:** For the final demand volumes, the flow rate required for each section is evaluated. The *OP2* evaluates hard constraints for the allocated PNC decision variables. In case of violation of hydraulic and technical feasibility, the proposed methodology will return to the *OP2* for an alternative configuration, thereby efficiently reducing algorithm space and time complexity by avoiding the unnecessary processing of the performance parameter module. For a feasible solution, the *OP2* will evaluate the value of performance parameter(s) and allocate them to the associated objective function. The objective function optimization continued till convergence criteria were attained, which can be the same solution for a set count of generations or reaching the maximum loop iterations count. On convergence or termination of *OP2* optimal search for PNC diameters for the given PS locations, the same *OP2* objective function value is shared with the *OP1*. Subsequently, the *OP1* continued to search for the further optimized value for a different set of intermediate pumping station locations and *OP2* re-initiated. In this methodology, both optimizers will have the same objective function by nested architecture while the interdependence of both variables is also ensured.
3) **Optimization Results:** The performance parameters for best objective functions are fetched for optimal PNC decision variables after termination of outer optimization analysis. The optimization's financial and environmental parameters outcomes include the investment value and operating cost throughout the analysis period, allowing for informed decision-making and efficient use of resources; calculation of the minimum tariff required by the owner to operate the pipeline, ensuring profitability and sustainability; estimation of the carbon footprint generated by the project investment and its operation, allowing for proactive measures to reduce the environmental impact of the pipeline network.

The variation in the demand volume of markets attached to the pipeline network is inseparable and perquisite to the PNC design. Hence, the sole dependence upon the *SHO* outcome which considers the final demand volume across the nodes, will not provide optimal PNC across the time horizon. A novel methodology is proposed in the subsequent section of multi-horizon optimization for optimally phasing the PNC according to the demand volume variations.

IV. MULTI-HORIZON OPTIMIZATION METHODOLOGY

The pipeline is a long-term and capital-intensive investment and it should be able to cater to demand variations across the multi-horizon period. Therefore, the implementation of a system-based Multi-Horizon Optimization (*MHO*) methodology for pipeline design empowers pipeline owners with the means to make informed strategic decisions regarding PNC expansion across the planning horizon. These decisions may involve the phasing of pumping stations, the installation of sectional parallel pipelines, or a combination of both, all guided by the systematic frameworks elucidated below. Furthermore, the proposed multi-horizon variation of the PNC minimizes the cost of the initial investment, reduces OPEX, and avoids the risk of pipeline overdesign due to several uncertainties such as technological disruption (introduction of electronic vehicles), & government policies (development of Special Economic Zone, closure of industry), and ensure optimal tariff as per the capacity utilization of the network. The primary aim of PNC design optimization is to find the most optimal values of the decision variables that either maximize or minimize the objective function, while also meeting a set of constraints. The evaluation of performance parameters in the *MHO* is more complex as the PNC undergoes variations over different time horizons. Figure 3 presents a general schematic overview of the process for the evaluation of multi-phase performance parameters and its corresponding optimization outcomes, based on phased pipeline network configurations as input across the time horizon by *MHO* analyzer. During the evaluation of net performance parameters, certain aspects related to pipeline construction remain constant across the time horizon calculations and are considered in the zeroth year, including linefill cost, tank cost, and initial phase PNC CAPEX, & its associated carbon emissions. On the other hand, operation-related components such as OPEX & its associated carbon emissions, are variable and calculated for each distinct PNC configuration throughout the multi-horizon period. Any variation in the PNC during the construction phasing will result in additional CAPEX, carbon emissions, & necessitates updates in subsequent depreciation and pipeline OPEX. Furthermore, the framework takes into account the variable cost and environmental coefficients over the time horizon duration. Finally, a comprehensive assessment of the overall cash-flow statement is conducted based on phased CAPEX, OPEX, depreciation, and their associated components, ultimately culminating in the determination of the pipeline's tariff. The *MHO* analyzer will play a pivotal role in assessing the outcomes of the *MHO* case study, as discussed in the later section.

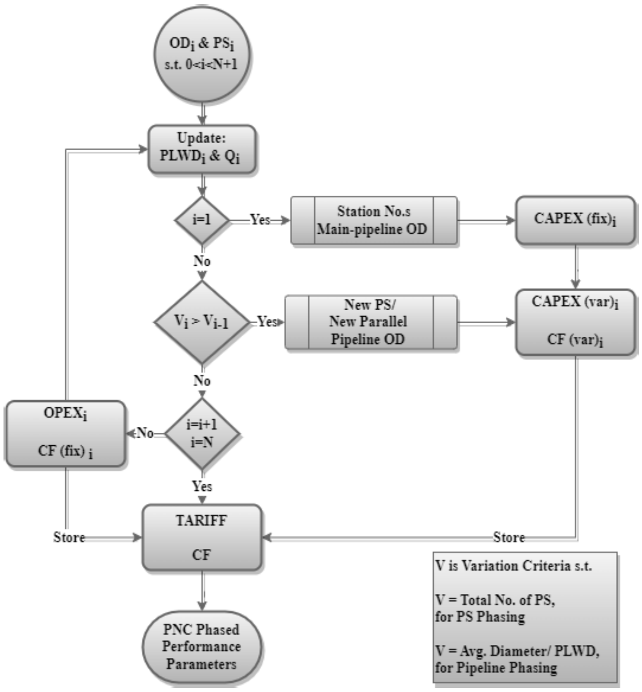

FIGURE 3. Multi horizon performance parameters analysis.

A. PIPELINE LAYING PHASING METHODOLOGY

In the Pipeline Laying *MHO* (*PLMHO*), an additional loop pipeline is laid parallel to the previously constructed main pipeline. This methodology is particularly implemented at sections where the main pipeline's capacity becomes technically infeasible to accommodate the increased flow rate and meet the demand volume of subsequent receiving stations following the initial phase of PNC construction. Figure 4 illustrates the PL*MHO* technique and it is briefly described below:

1) **First Phase Optimization:** Based on the user input on the first phase year in p^{th} year, the *SHO* optimizers (*OP1* & *OP2*) will envisage both optimal PNC decision variables constituting mainline pipe and pumping stations for the estimated demand volumes.
2) **Pipeline Laying Phasing Optimization:** For each subsequent phase, the PL*MHO* optimizer (*OP3*) will check the technical feasibility for the revised demand volumes, and change the PNC if it is found infeasible. The *OP3* will search for the additional loop pipeline diameters across the existing PNC sections to overcome the pressure loss bottlenecks, without changing the number of the Pumping Station (*PS*). The equivalent diameter for i^{th} section is mentioned in the equation (13) below [52]. For the search for a new optimal loop pipeline from the multiple possible PNC outcomes, the *OP3* considers minimum PLWD as an objective function along with a penalty function for hydraulically infeasible solutions.

$$D_e = \left(\sum_{i=1}^{n} \left(\frac{f_e}{f_i}\right)^{2.5} \times {D_i}^{2.5} \right)^{0.4} \tag{13}$$

3) ***PLMHO* Result Analysis:** In the context of the *PLMHO*, the main factors that undergo significant changes are related to the loop pipelines and their

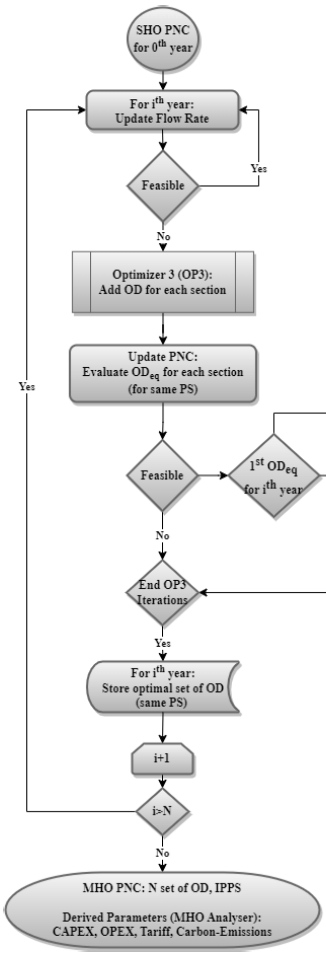

FIGURE 4. **Pipeline laying multi horizon optimization methodology.**

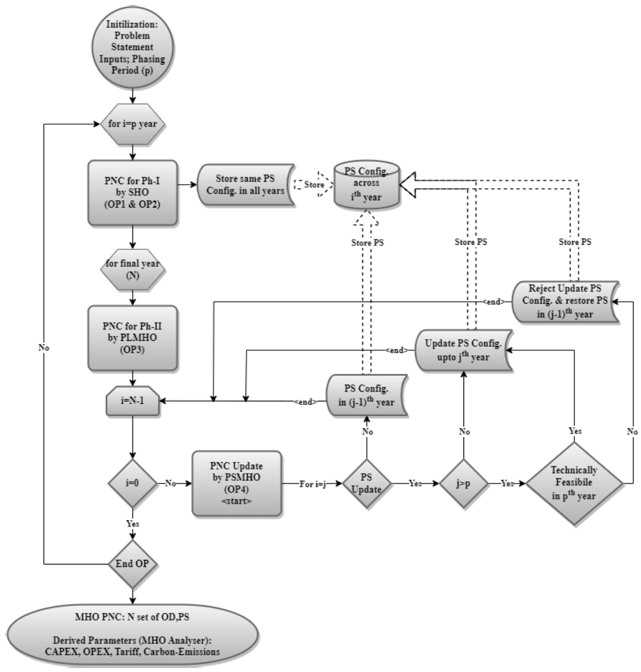

FIGURE 5. **Pumping station multi horizon optimization methodology.**

associated systems. These include considerations such as cathodic protection system and survey costs, laying expenses, right-of-way (RoU) compensations, line-pipe costs, line fill costs, and the updated operations & maintenance expenses. Furthermore, major carbon emission variables are introduced, accounting for additional steel production, considering varying carbon emission coefficients for the loop pipeline and its transportation to the site, as well as RoU soil excavation and pipeline installation. The *MHO* analyzer performs a comprehensive assessment of the cash flow across the time horizon, factoring in varying elements such as CAPEX, OPEX, depreciation, and taxes. Based on the cash flow analysis, the tariff is determined. Additionally, the *MHO* analyzer calculates overall carbon emissions and evaluates the discount factored overall cost. This integrated analysis provides a holistic view of the financial, environmental, and operational aspects of the pipeline project over time.

The impact of the user selection of the initial phase year is also studied and discussed in a subsequent section.

B. PUMPING STATION PHASING METHODOLOGY

In the Pumping Station *MHO* (*PSMHO*), the key strategy involves deferring the construction of the intermediate pumping station until a later year, wherein the PNC remains technically feasible even without its presence. The *PSMHO* methodology aids the pipeline owners in making a judicious decision regarding the optimal timing for the installation of pumping stations *PS*. This ensures that these stations are brought into operation in alignment with the actual operational demands of the pipeline network, thus minimizing investment risks arising from unforeseen variations in initial demand forecasts. Hence, this approach not only enhances the financial aspects of the project but also contributes to environmental sustainability and operational efficiency. Figure 5 illustrates the *PSMHO* methodology, which is briefly outlined as follows:

1) **Final PNC:** The *SHO* optimizers (*OP1* & *OP2*) will envisage optimal PNC decision variables for the final estimated demand volumes.
2) ***PS* Phasing Optimization:** Following the above step, the requirement of every intermediate pumping station(s), is re-evaluated in different time horizons, in reverse order. This reassessment is carried out by a dedicated optimizer (*OP4*) without any changes to the pipeline diameters. In a particular year, the number of pumping station(s) remains constant unless it is determined that their removal would still yield a technically feasible solution. In such cases, the construction of the pumping station(s) is deferred to a subsequent year. The objective function aims to minimize the number of pumping station(s) in a particular

horizon while also considering technical feasibility as its penalty function. It's crucial to highlight that, in contrast to the previously discussed *PSMHO*, which involves significant time lapses in the subsequently fixed pipeline laying phases, *PSMHO* have flexibility which allows pumping station(s) construction phasing for each year so that its subsequent phased investment can be shifted anywhere from the near commissioning year to the farthest year in the time horizon.

3) ***PSMHO* Result Analysis:** In *PSMHO* analysis, variable CAPEX components are due to additional process area required for new pumping station(s) facilities including mainline pumps, HVAC system, basket filters, mass flow meters, sump tank & its pump, corrosion inhibition system, fire-protection system, and pumping station's associated civil, mechanical & instrumentation costs. However, due to the expected difficulty in land purchase in future horizons, future pumping station land cost is considered in the initial phase. Similarly, major carbon emission variables are from the construction of a new pumping station in place of an intermediate node and emissions from its operations including mainline pumps. Subsequently, the *MHO* analyzer will consolidate the impact of these variables and provide final performance parameter values.

C. PIPELINE LAYING & PUMPING STATION PHASING METHODOLOGY

In *PLMHO* and *PSMHO*, the loop pipeline is laid across the initial pipeline, and the non-pumping station is converted to the pumping station across the PNC respectively to cater to the additional hydraulic requirements bottlenecks across the PNC due to variation in the demand volumes. Their optimizers will exclusively search for a single optimal decision variable, without changing the alternative decision variable initially derived from the *SHO*. To overcome this drawback and in search of further optimized results, a simple but effective Pipeline Laying & Pumping Station *MHO* methodology is illustrated in Figure 6 and described below:

1) **First Phase Optimization:** The *SHO* solution will be evaluated for the initial phase period by using its optimizers (*OP1* & *OP2*).
2) **Forward Horizon Optimization:** Subsequent PNC will be evaluated by pipeline laying by using *PLMHO* optimizer (*OP3*) for the end-year volumes of the subsequent phases.
3) **Reverse Horizon Optimization:** For the given set of *PLMHO*-based PNCs across the provided phase horizons, *PSMHO* will be applied in the reverse time horizon order. The *PSMHO* (*OP4*) will check the requirement of intermediate pumping stations in reverse chronological order and subsequently postpone the construction of such stations to future horizons, thus reducing the number of PS stations in the initial

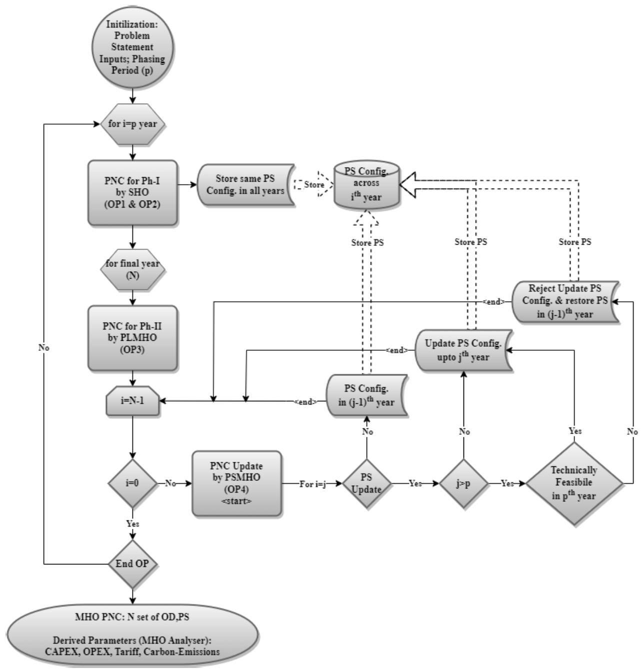

FIGURE 6. **Pipeline laying & pumping station multi horizon optimization methodology.**

years. This is further depending upon the the particular *PSMHO* phasing year (j^{th} year), as outlined below:

a) Condition 1 - *PS* not updated: Number of the pumping station(s) are same in $(j-1)^{th}$ value
b) Condition 2 - *PS* updated and j^{th} year $< p^{th}$ year: Pumping station(s) phasing updated till j^{th} year with lesser number of pumping stations value
c) Condition 3 - *PS* updated and j^{th} year $\geqslant p^{th}$ year:
   i) For the updated *PS*, PNC is technically feasible for p^{th} year also: The outcome of *PSMHO* phasing is admissible and lesser number of pumping station(s) updated till j^{th} year
   ii) For the updated *PS*, PNC is technically infeasible for p^{th} year also: The outcomes of *PSMHO* phasing is rejected for all PNC upto j^{th} year and the number & location of the pumping station(s) are reverted to their values from the $(j-1)^{th}$ year.

4) ***PLPSMHO* Result Analysis:** The *PLPSMHO* results in highly dynamic commercial and environmental parameters ensuring the most optimal PNC design outcome. The performance parameters will be evaluated for the final set of the PNC across the multi-horizon period by *MHO* analyzer.

V. RESULTS AND DISCUSSION

The article highlights the need for efficient and prudent system-based decision-making in pipeline network design to avoid sub-optimal costs and unnecessary burdens on end-users due to inflated tariff costs resulting from unreliable pipeline capacity. The proposed PNC optimization framework is a much-needed solution to address the intricacies and scale of this multifaceted problem. The PNC mathematical models and their optimization are implemented and executed in Python 3.8, a versatile programming language well-suited for simulation modeling due to its extensive libraries, swift execution, and user-friendly interface. The proposed optimization framework involves a two-tiered optimization process, with the Boolean Particle Swarm Optimization (BPSO) optimizer employed in the outer loop, which involves optimizing the locations and quantities of intermediate pumping stations. Meanwhile, the inner loop, focused on optimizing pipeline diameters based on specific pumping station configurations, was executed using a customized optimizer based on the objective function type. For mono-objective and mono-to-multi-objective functions (CAPEX, OPEX, Tariff, and carbon emissions), the Genetic Algorithm (GA) optimizer was deployed. In cases involving multi-objective functions, specifically combinations like Overall-cost & Carbon-emissions (*OCMOF*) and Tariff & Carbon-emissions (*TCMOF*), the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) optimizer was employed. This sophisticated optimizer generates a collection of optimal solutions known as Pareto Optimal Solutions, allowing us to select the most suitable solution based on predefined equal weightage attributed to each conflicting performance parameter.

Further two case studies are considered for empirical analysis of China Multi Product Pipeline for *SHO* and Central India Pipeline for *MHO* methodologies vis-à -vis their reference PNC, shedding light on their practical efficacy and benefits. In both case studies, the pipeline material conforms to the API 5L X-70 standards, and all associated facilities, including valves, joints, and flanges, adhere to the 600# class pressure ratings. The pipeline roughness is set at $40\mu m$, and an additional $0.5mm$ corrosion allowance is incorporated into the pipeline thickness. The specific details pertaining to each problem statement are elaborated in their respective sections below.

A. CASE STUDY 1 FOR SHO: CHINA MULTIPRODUCT PIPELINE

The efficacy of the proposed *SHO* methodology is assessed using the China Multi-product Pipeline (CMPL) problem statement, as previously outlined in [41], incorporating the mathematical model referenced in [62] for empirical analysis. Utilizing the reference PNC's 40 decision variables and initialization data, its performance metrics are evaluated and mentioned in Table 1.

The impact of distinct objective functions on the *SHO* results, and these findings are illustrated in Figure 7 to facilitate a comprehensive comparative analysis and comprehensively discussed below.

1) MONO OBJECTIVE FUNCTIONS

CAPEX: It's important to highlight that relying solely on CAPEX as a performance parameter within the objective function, a common practice among pipeline design engineers, may indeed align with the pipeline owner's investment optimization goals but could inadvertently impose a substantial burden on end-customers in terms of elevated operating costs and place undue stress on the environment. As highlighted in Table 2, when the objective function is CAPEX-based, the resulting PNC demonstrates the lowest CAPEX value at 33.51 Billion INR, but this advantage comes at the cost of a substantial 28.63% increase in OPEX. This, in turn, leads to the second-highest overall cost increase, amounting to 6.71%, but with the third-lowest tariff value, standing at 1138 INR/MT. Hence, it's worth noting that while both overall cost and tariff serve as indicators of commercial aspects, they exhibit disparate sensitivities to variables and performance parameters. Another critical observation emerges in the form of a significant reduction in PLWD by −10.94% with the inclusion of an additional pumping station. This reduction indicates that the outcome results in the utilization of smaller pipe diameters, consequently necessitating more pumping stations. However, it is

TABLE 1. Reference CMPL PNC & performance parameters.

Reference Pipeline Network Configuration ([41])						
Discrete ID (in inch):	**1-3:** 22", **4-6:** 18", **7-9:** 16", **10-18:** 13.21", **19-20:** 10.75"					
PS Nodes:	1, 4, 10, 14, 17					
Performance Parameters						
PLWD	PS No.	CAPEX	OPEX	Overall Cost	Tariff	CE
15.18"	5	36.35	24.09	60.44	1138	616

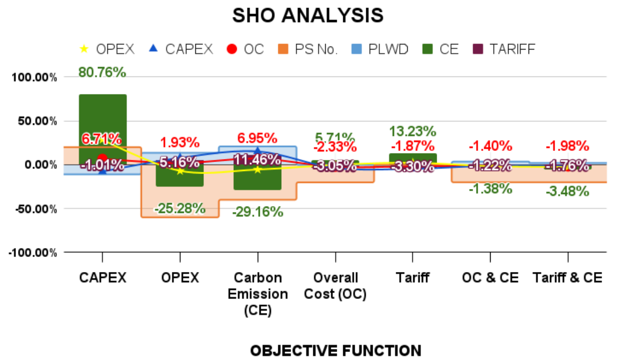

FIGURE 7. Impact of objective function on *SHO*.

TABLE 2. CMPL *SHO* performance for different objective functions.

Objective Function	PLWD (in inch)	PS No.	CAPEX (in B INR)	OPEX (in B INR)	Overall Cost (in B INR)	Tariff (in INR / MT)	CE (in CO2 GT)
CAPEX	13.52"	6	33.51	30.99	64.49	1126	1113
OPEX	17.24"	2	39.19	22.41	61.60	1126	460
Carbon Emision (CE)	18.36"	3	41.86	22.77	64.64	1268	436
Overall Cost (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

important to consider the broader implications of this choice, particularly regarding the environment. The CAPEX-based PNC exhibits the highest increase in carbon emissions, surging by 80.76%. Consequently, considering the broader *TEC* context, it becomes apparent that relying solely on CAPEX as the sole performance parameter in the objective function is not a recommended practice.

Furthermore, research has unveiled that the proposed framework, which draws inspiration from real-world industrial practices, offers substantial untapped potential for further optimization by considering the prospect of constructing intermediate pumping stations at *SV* and *IPS* nodes. In the context of our case study, particularly with the CAPEX-based objective function, we observed a noteworthy outcome: the construction of pumping stations in nodes 3, 6, and 12, a result that previous research frameworks might have overlooked. This underscores the framework's ability to uncover more valuable and previously unexplored optimization-efficient solutions.

OPEX: While it's atypical to consider OPEX as the sole objective function in PNC design optimization, this practice is commonly employed to address post-commissioning operational challenges in the pipeline industry. The OPEX objective function presents a unique dynamic, often operating in trade-off with the CAPEX performance parameters, leading to contrasting PNC outcomes. Notably, the OPEX-based objective function results in the second-highest increment in PLWD of 13.52%, achieved with only two pumping stations including the dispatch station. It's worth noting that constructing a larger diameter upfront might not always be the most prudent strategy, particularly in cases where significant demand volume variations are anticipated in order to mitigate design risks effectively. As anticipated, this leads to the lowest overall OPEX value (22.41 Billion INR), albeit with the second-highest increase in CAPEX (7.82%). Consequently, the overall cost experiences a similar increase, amounting to 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 exhibits the tariff's second-largest increase (5.16%) but also records the second-largest reduction in carbon emissions (-25.28%). Moreover, it's crucial to recognize 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 not be disregarded. From the sensitivity analysis of the mono-objective functions on the PNC design optimization, it is inferred that relying solely on mono-objective functions, whether based on CAPEX or OPEX, may not yield a balanced PNC solution that accounts for the complete *TEC* aspects. The combination of both parameters is necessary to achieve this balance, as discussed in the following sections.

2) MONO-TO-MULTI OBJECTIVE FUNCTIONS

Carbon-Emissions: For the first time, this study examines pipeline project carbon emissions as the singular objective function in PNC design optimization, encompassing elements from both pipeline construction and operations. The outcomes underscore the possibility of achieving a remarkable reduction of 180 CO2 GT (-29.16%) when compared to the reference PNC. A substantial 11.68% increase in tariff value is also observed. The resulting performance parameters align closely with those of an OPEX-based objective function, except OPEX-based objective functions tend to emphasize better commercial outcomes. It also prioritizes the diameter decision variable vis-à -vis the number of pumping stations. Hence, similar to the mono-objective function, carbon emissions should be considered in tandem with other performance parameters within a broader multi-objective function methodology. This approach ensures a more comprehensive evaluation and balance across various aspects of PNC design optimization.

Overall Cost: Optimizing the overall cost objective function stands as a conventional and prevalent practice in both the PNC design optimization literature and industry applications. This approach sets itself apart from other objective functions by achieving a notable reduction in both PLWD and the number of pumping stations. This performance parameter amalgamates the CAPEX and OPEX dimensions into a unified objective function, effectively addressing their inherent trade-off dynamics. As a result of a dual reduction, with CAPEX decreasing by −3.75% and OPEX by −0.19%, culminating in the lowest overall cost amounting to 59.03 billion INR, which represents a -2.33% reduction, with a more prominent contribution from the CAPEX components. Furthermore, this reduction in CAPEX translates to lower initial-year cash flows, resulting in the second-lowest tariff, which stands at 1103 INR/MT (−3.05%). However, it's essential to acknowledge that this approach triggers an increase in carbon emissions by 5.71%. As a result, 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 hold paramount importance in the practical design of PNC & regulatory requirements from a financial perspective, and this research introduces a novel approach by incorporating tariff-based performance parameters. These parameters offer a more comprehensive evaluation of the financial aspects, encompassing components like EIA studies cost, mitigation cost (C_{EN}), EPMC cost (C_{EP}), start-up commissioning & owner expenses (C_{SO}), spare cost (C_{SP}), and contingency cost (C_C) and additionally, it accounts the implications of demand volume escalation, thus enriching the optimization process, as detailed in [62]. It results in a −1.42% reduction in PLWD, while the number of pumping stations remains consistent with the reference PNC. The range of 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 fulfills 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 crucial to acknowledge that the tariff-based objective function does come with a trade-off–a higher level of carbon emissions (13.23%). Hence, 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*) similar to *OCMOF*.

3) MULTI OBJECTIVE FUNCTIONS

Overall Cost and Carbon-emission: The overall cost and carbon-emissions-based objective functions exhibit a trade-off relationship and hence, are indispensable to meet the complete requirement of *TEC* aspects. In the context of the *OCMOF*, the optimizer yields a notable reduction in carbon emissions, reaching a more environmentally friendly, carbon-neutral PNC outcome curtailed to −1.38%. However, this achievement comes at the expense of elevated commercial performance parameters, notably an increase of 560 Million INR in overall cost and 21 INR/MT in tariff. Further, this reduction in carbon emissions is facilitated by a slight increase in PLWD, while maintaining the same number of pumping stations as observed in the overall cost-based objective function. This indicates that the *OCMOF* has the potential to offer a better trade-off between financial and environmental considerations in the PNC design optimization.

Tariff and Carbon-Emission: In the process of PNC design optimization, it is of paramount importance to factor in the tariff performance parameter in tandem with carbon emissions. The Tariff & Carbon-emission based Multi-objective Function (*TCMOF*) is crucial to avoid imposing undue financial burdens on users due to elevated OPEX and to mitigate environmental degradation as observed in the tariff-based objective function. The *TCMOF* optimizer achieves this goal by increasing the PLWD while simultaneously decreasing the pumping stations. Notably, the *TCMOF* yields the most robust, balanced, and sustainable solution for all *TEC* performance parameters, even surpassing the *OCMOF* as mentioned in Table 2. Therefore, *TCMOF* takes precedence in the subsequent sections, allowing for a thorough scrutinizing of its impact on performance parameters across various types of Multi-Horizon Optimization (*MHO*) methodologies used for problem statements featuring variable demand volume.

B. CASE STUDY 2 FOR MHO: CENTRAL INDIA PIPELINE

An eminent Oil Marketing Company in India is embarking on a substantial project involving the construction of a 356 km long, linear cross-country multi-product Central India Pipeline (CIPL). This pipeline is designed with an 18-inch diameter with an average design factor of 0.65 and a single pumping station at the dispatch location. This pipeline has been designed for transportation of Motor Spirit (MS) and High-Speed Diesel (HSD) and will experience an incremental increase in total demand volume from 2.2 MMTPA to 3.4 MMTPA in the initial 13 years after commissioning. For the remaining 11 years of the designated time horizon, the demand volume remains constant. The project's performance parameters are derived from the *TEC* models proposed by [62] with initialization inputs from [68], and a target Internal Rate of Return (IRR) of 12%. The assessed performance parameter values for these inputs are mentioned in Table 3. An essential distinction to note is that, unlike the previous CMPL problem statement used for various *SHO* analyses, the CIPL has varying volume and elevation profiles. This real-world context adds a unique dimension to the study, offering insights into the practical challenges and dynamics of PNC design. The CIPL problem statement encompassing all 24 decision variables is utilized to further evaluate the effectiveness of the proposed *SHO* & assessment of different types of *MHO* methodologies by comparing the results with the actual PNC performance parameters. The results of various methodologies are tabulated in Table 3 and comprehensively discussed below.

1) CIPL SHO OUTCOME

In the evaluation of *SHO*, the final year demand volume of the CIPL problem statement is considered throughout the time horizon. In this analysis, it is found with the addition of a pumping station at node 8 (*SV6*), there is a significant reduction in pipeline diameter to 14 inches (-22.22%) across its entire length. This strategic modification of the PNC yields significant reductions in both overall costs for the owner, to the tune of −4.91% (equivalent to 20.52 Billion INR), and tariffs for the regulator, with a substantial −15.96% decrease (711 INR/MT). While this optimization delivers compelling financial benefits, it's essential to mention that it also leads to a notable increase in carbon emissions, which rise significantly by 178.57% (equivalent to 312 CO_2 GT). The CIPL is suitable for a *MHO* problem statement due to demand volume variations and with the possible phasing of the pipeline construction, the *SHO* outcome becomes sub-optimal. Hence, further *MHO* analysis is performed for the CIPL problem statement.

2) PSMHO OUTCOME

In this context, the PNC outcome under the *PSMHO* aligns with that of *SHO* outcome, with *IPPS* introduced in the 7^{th} year after commissioning. This strategic approach not only leads to further reductions in overall costs for the owner, amounting to a substantial −5.61% (equivalent to 20.37 Billion INR), and tariffs for the regulator, with a significant −16.47% decrease (708 INR/MT), but also results in slightly lower carbon emissions, measuring 309 CO_2 GT. These findings underscore the effectiveness of the *PSMHO* approach in achieving a well-balanced *TEC* outcome.

3) PLMHO OUTCOME

In comparison to *PSMHO* phasing, pipeline laying phasing is difficult as it is prone to a myriad of external factors,

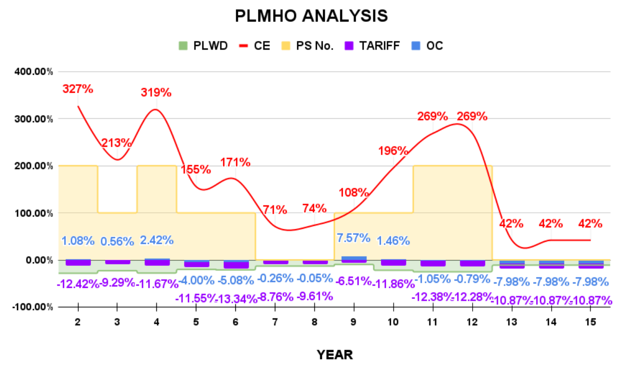

FIGURE 8. Impact of initial phasing year selection on *PLMHO*.

including social, political, environmental, and regulatory considerations. Hence, for the CIPL problem statement, the two-stage *PLMHO* approach is considered. Additional analysis of *PLMHO* methodology has been carried out to elucidate the impact of the phasing year on the final outcome as depicted in Figure 8. From the overall perspective, the implementation of *PLMHO* generally leads to a reduction in tariff rates; however, for certain cases, it is also accompanied by an increase in the overall cost. The carbon emissions performance parameter consistently maintains a relatively high correlation with the number of intermediate pumping stations. However, it reaches notably high values at the extreme ends of the analysis period, primarily due to the overdesign of the PNC for either phase. Remarkably, in the 7^{th} year, when the initial phase constitutes approximately 80% of the total volume, *PLMHO* emerges as the most economically and environmentally viable solution, with the least number of pumping stations. The *PLMHO* approach leads to a marginal reduction in the overall cost (-0.26%) and a notable decrease in tariff (-8.76%). However, it is accompanied by a higher carbon emission of 191 CO2 GT, although it's worth noting that this approach results in the second lowest carbon emissions among the various optimization methodologies.

The *PLMHO* approach implicitly yields *SHO* outcomes when the demand volume nearly reaches its final value. In the CIPL problem statement, the *PLMHO*-derived *SHO* (*PLMHO-SHO*) PNC outcome features 16-inch diameters across all sections without any pipeline laying phasing and intermediate pumping stations. Due to the inherent property of *PLMHO* on favoring higher PLWD in comparison to actual *SHO*. Consequently, this divergence in PNC design results in the lowest overall cost (-3.24%). However, this reduction is accompanied by a 4.22% increase in the tariff. Notably, the *PLMHO* methodology provides PNC outcomes with the lowest carbon emissions among the other methodologies, thus presenting a substantial environmental benefit.

4) PLPSMHO OUTCOME

For the given problem statement, the optimal *PLMHO* PNC outcome was noted in the 7^{th} year due to the rapid growth demand volume rate within a relatively short time span. Nevertheless, it's important to emphasize that such frequent laying of parallel pipelines across the mainline sections within a short time frame is atypically industrial practice. Therefore, in the context of examining the *PLPSMHO* approach, the 11^{th} year has been selected as the time frame for the parallel pipelines across the mainline sections. In comparison to *PLMHO* outcome in 11^{th} year, *PLPSMHO* has phased the intermediate pumping stations construction in the 3^{rd} and 10^{th} years for nodes 4 and 9, respectively. This results in a modest reduction in an overall cost of -0.41% (90 Million INR), 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 *PLMHO* methodology achieved in the 7^{th} year, it's noteworthy that although the *PLPSMHO* approach exhibits higher carbon emissions, its overall cost and tariff reductions of -1.40% and -6.80%, respectively.

TABLE 3. ***MHO*** **CIPL PNC performance.**

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
PLPSMHO (n=11)	13.48"	3	21.27	713	407

VI. CONCLUSION

This article underscores the dynamic nature of pipeline construction and the various factors that influence decision-making. By carefully evaluating the suitability of different methodologies, stakeholders can make informed decisions to balance financial, environmental, and practical considerations in pipeline network design. The proposed PNC design optimization framework ultimately contributes to the successful and sustainable development of pipeline systems meeting the requirements of owner, user, and regulators.

During the investigation of the CMPL *SHO* study consisting of reference PNC derived from the design optimization technique proposed by [41], a meticulous analysis of performance parameters' sensitivities in the context of various objective functions has revealed several noteworthy observations:

1) **Enhanced PNC Design Optimization:** The compelling outcomes reveal the feasibility of achieving substantial further reductions in CAPEX, OPEX, and overall cost in comparison to the already optimized reference PNC, amounting to impressive savings of up to 2.84 Billion INR, 1.68 Billion INR, 1.41 Billion INR respectively to the owner. Further, a significant reduction in tariff rates up to 38 INR/MT over the analysis period and a noteworthy reduction of 180 CO2 GT carbon emissions, effectively aligning with regulatory requirements.
2) **Distinct Sensitivity Metrics:** While both overall cost and tariff pertain to commercial aspects, they exhibit unique sensitivities to various variables and performance parameters. This highlights the importance

of different objective functions for optimization to align with project-specific goals. Further, the tariff and carbon-emission performance parameters have demonstrated a higher level of responsiveness in sensitivity analysis compared to the classical CAPEX, OPEX, and overall cost performance parameters. This makes them particularly well-suited for future sensitivity studies in the design of Pipeline Network Configurations (PNC).

3) **Expansion of Optimizer Search Space:** The proposed framework, rooted in real industrial practices, has revealed significant untapped potential within already optimized reference PNC by expanding the optimizer's search space to encompass the entire range of available commercial diameters along with velocity boundary conditions and exploring intermediate stations such as *SV* and *IPS* as viable nodes for intermediate pumping station construction. This phenomenon is also evident in the examination of the CAPEX-based objective function case study, in which intermediate pumping stations have been installed at nodes 3, 6, and 12 where *SV* station present in the original PNC, aspects that could have been inadvertently neglected in previous research frameworks.
4) **Correlations in Performance Parameters:** Notably, OPEX and carbon emissions show a direct correlation with PLWD or diameter decision variables. Similarly, CAPEX and tariffs exhibit connections with the number of pumping station decision variables. These relationships emphasize the intricate interplay between various performance parameters in the PNC design.

For the examination of the *MHO* methodologies, a case study of the CIPL is scrutinized, having varying demand and elevation profiles. These methodologies have not been extensively discussed in prior work, making this study not only an elaboration for future reference but also an evaluation of their effectiveness for real-case scenarios. The brief summary of CIPL *SHO* and *MHO* examinations is mentioned below:

1) ***SHO*** **Sub-optimality:** In the context of varying demand volumes, the *SHO* outcome is found to be sub-optimal, necessitating a comprehensive evaluation of various *MHO* methodologies. In the CIPL case study, *PSMHO* demonstrates superior (*TEC*) outcomes compared to its *SHO* outcome by strategically scheduling the installation of intermediate pumping stations in the 7^{th} year. In comparison to the original CIPL PNC, *PSMHO* demonstrates significant reductions in overall cost and tariff rates by −5.61% and −16.47%, respectively.
2) **Impact of Phase Selection in** ***PLMHO*****:** The study evaluates the application of the two-stage *PLMHO* to the CIPL problem statement. It's observed that to achieve a balanced *TEC* outcome, the initial phase year for PNC design optimization should be considered when demand volumes approximate 80% of the total demand.
3) **Combined** ***PLMHO*** **and** ***PSMHO*** **Methodology:** *PLPSMHO* optimization strategy results in a substantial cost savings of 90 Million INR for the owner, a notable reduction of −3.85% in tariff rates, and a commendable 6 CO2 GT reduction in carbon emissions for *PLMHO* configurations involving pipeline laying in the tenth year and having intermediate pumping stations.
4) **Tariff Calculation Standardization:** Irrespective of the type of PNC design optimization approach, improvements in tariff evaluation have been observed in all results. This highlights the urgent need for standardizing tariff calculations by regulators to prevent imposing undue burdens on pipeline users and end customers.

In essence, this study not only reveals the extensive untapped potential for pipeline network optimization but also emphasizes the importance of selecting the most appropriate objective functions and methodologies to achieve a balance between commercial viability and environmental sustainability in the context of real-world pipeline design. The proposed framework provides an accurate and reliable approach to dealing with the PNC optimization problem, including the strategic placement of pumping stations, optimal phasing period for pipeline laying, and meeting the regulatory prerequisites. Consequently, regulatory bodies can leverage this tool to evaluate permissible tariff rates in the best interest of the public. Therefore, this research serves as a foundation for future optimization work, as the proposed framework can be further used with upcoming cutting-edge optimizers to generate even more insights and can be extended to solve more complex & challenging problems ensuring both commercial efficacy and environmental sustainability.

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ABBREVIATIONS

The following symbols are used in this article:

A_i	Area of i^{th} section (m^2)
B_{IPPS_i}	Intermediate Pumping Station location at i^{th} node (0,1)

B_{IPPS_i}	Intermediate Pumping-cum-Receiving 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_T	Trench width (m)
C_{AX}	Auxiliary Energy Consumption Carbon Emission Coefficient (CO_2 GT)
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_{IN}	Insurance Cost Coefficient (Billion INR PA)
C_{LF}	Line-fill Product Cost Coefficient (Billion INR/KL)
C_{N-PS}	Construction of New Pumping Station Carbon Emission Coefficient (CO_2 GT)
C_{OCP}	Cathodic Protection Cost Coefficient (Billion INR PA)
C_{OM-P}	Operation & Maintenance Cost of Pipeline Coefficient (% PA)
C_{OM-S}	Operation & Maintenance Cost of Stations Coefficient (% PA)
C_{PC}	Pipe Steel Cost Coefficient (Billion INR/kg)
C_{RD}	Road Transportation Carbon Emission Coefficient (CO_2 GT/ km/MT)
C_{SCE}	Steel Carbon Emission Coefficient (CO_2 GT/MT TCS)
C_{SE}	Soil Erosion Carbon Emission Coefficient (CO_2GT/m^3)
C_{SO}	Start-up Commissioning & Owner's Expenses Cost Coefficient (%)
C_{SOC}	Soil Type Coefficient
C_{SP}	Spare Cost Coefficient (%)
C_{SX}	RoU Excavation Carbon Emission Coefficient
C_{TNC}	Pipeline Transportation & Coating Cost Coefficient (% of C_{PC})
C_C	Contingency Cost Coefficient (%)
$CAPEX$	Total Capital Cost of Pipeline Project (Billion INR)
$CAPEX_t$	Capital Cost of Pipeline Project in t^{th} year (Billion INR)
CE	Total Carbon Emission (CO_2 GT)
cpi	Consumer Price Index (%)
D_e	Equivalent Diameter of parallel lines in i^{th} section
D_i	Internal Diameter in i^{th} section
df	Real Discount Factor (%)
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	Equivalent friction factor of parallel lines in i^{th} section
f_i	Friction factor at i^{th} node
γ_{ECE}	Dynamic Factor for Electrical Carbon Emission (%)
γ_{SCE}	Dynamic Factor for Steel Carbon Emission (%)
h_{T_i}	Trench height in i^{th} section (m)
irr	Internal Rate of Return (%)
IT_t	Income Tax in t^{th} year (Billion INR)
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)
N	Analysis Period (years)
O_E	Total Operating Cost of Energy Consumption (Billion INR PA)
O_L	Total Operating Cost of Land (Billion INR PA)
O_M	Total Operating Cost of Manpower & Admin. Coefficient (Billion INR PA)
O_P	Pipeline Cost (Billion INR)
O_S	Total Cost of all Stations (Billion INR)
OC	Overall Cost (Billion INR)
OD_l	Outer Diameter of l^{th} section (m)
op_E	Operating Cost Escalation (%)
$OPEX$	Total Operating Cost (Billion INR)
$OPEX_t$	Operating Cost in t^{th} period (Billion INR PA)
P_{B_m}	Minimum Back-pressure required at m^{th} node (Kg/cm^2)
P_{D_l}	Discharge Pressure required at l^{th} node (Kg/cm^2)
P_{E_i}	Elevation Pressure at i^{th} section (Kg/cm^2)
P_{F_i}	Friction Loss at i^{th} section (Kg/cm^2)
P_I	Internal Pressure (Kg/cm^2)
$P_{KW_{it}}$	Pump Power of i^{th} node in t^{th} year (KW)
P_{M_i}	Minor Pressure Loss at i^{th} section (Kg/cm^2)
PH_t	CAPEX Phasing Ratio in t^{th} year (%)
Q_l	Pump Rated Flow Rate in l^{th} section (KL/hr)
ρ_s	Steel Density (kg/m^3)
S_{P_t}	Steel Line Pipe Quantity (Kg) in t^{th} year (kg)
S_{T_t}	Steel required for Tank in t^{th} year (kg)
S_P	Steel Line Pipe Quantity (Kg)
T	Pipeline Tariff (INR/MT)
t_l	Pipe Thickness of l^{th} section (m)
T_O	Total Pumps Operational Hours during Analysis Period (hours)
t_v	Volume Escalation
ta_E	Tariff Escalation (%)
V	Product Demand Volume (MT)
v_E	Economical Velocity (m/s)
V_i	Demand Volume in i^{th} section
v_l	Velocity in l^{th} section (m/s)
v_U	Upper-limit of Velocity (m/s)
w_C	Coating Width (m)

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