

STATE OF THE ART FOR THE OPTIMIZATION AND SIMULATION OF THE DISTRIBUTION OF HYDROCARBONS

Emilio Sampayo Trujillo^(a), Idalia Flores De La Mota^(b)

^(a) PEMEX, Exploración y Producción ^(b) Faculty of Engineering, UNAM

^(a)emilio.sampayo@pemex.com, ^(b)idalia@unam.mx

ABSTRACT

Hydrocarbons distribution networks are strategic for the oil industry. That is why the research being presented in this article focuses on thoroughly reviewing everything that has been developed on the subject in different parts of the world over the last fifteen years. The reviewed articles have been classified according to the models that were built, the methods used to solve said models and the approach that has been developed. Because of the characteristics of the problem in general, there is more research available that uses mathematical models and finds the solution with different optimization methods. Secondly, though no less important we found simulation models for studying some aspects that are differentiated from the optimization models.

Keywords: Hydrocarbons, distribution networks, optimization, simulation

1. INTRODUCTION

Petróleos Mexicanos is currently one of the 100 largest companies in the world. Its most profitable business is oil exploration and production which is done through Pemex Exploración y Producción (PEP), the only company in the Pemex Group with a special tax régime.

In 2004 PEP was the third biggest oil producer in the world with a yearly average of 3.4 million de barrels a day, of which 2.1 million came from Cantarell, one of the highest producing oil fields in the world. Since then, Cantarell has suffered a natural decline and nowadays only produces about 200 thousand barrels a day.

The challenge for Pemex Exploración y Producción is to replace the fall in Cantarell's production, stabilize production and eventually profitably, surely and sustainably increase the platform.

It also faces the challenge of adjusting the cost structure to a scenario of low prices and the historic opportunity to use all the tools provided by the Energy Reform, in other words, it can develop a similar operation to all the other oil companies in the world, which will allow it to share technical, technological and financial risks throughout the value chain.

To achieve this, Pemex put into operation its Business Plan, which it uses to encourage alliances to be created throughout Pemex's value chain as a mechanism for increasing its investments and efficiency. For example,

Petróleos Mexicanos and the Australian company, BHP Billiton, signed the license agreement for the development of the deepwater Trion block.

This is the first partnership for exploration and production via farm-out or partnership that Pemex has entered in all its history, taking advantage of the mechanisms and flexibility it is granted under the Energy Reform. The Trion block, discovered by Pemex in 2012, has total 3P reserves of 485 million barrels of equivalent crude oil, so there is certainty about its commercial viability.

However, it must be pointed out that oil acquires its true economic value on being sold, meaning that the hydrocarbons distribution process, which starts at the production complexes and ends at the points of sale, is particularly important.

Nowadays there is no tool or procedure that makes it possible to analyze the overall economic value that can be obtained through Pemex Exploración y Producción's hydrocarbons distribution, collection and treatment infrastructure, which it makes available to the Oil Concessions and new operators, if necessary.

This article gives the state of the art for the different techniques that have developed solutions over the last eighteen years for the distribution of gas main and, in some cases, crude oil. This bibliographic review basically deals with the optimization and simulation models used, which will allow us to frame the contribution to the optimization and simulation of PEMEX's Hydrocarbons Distribution System that we intend to set forth in a later article. Said model will allow us to generate higher economic value by optimizing mixtures.

The proposed methodological basis is based on optimization theories and techniques, mixed integer programming, which is suitable for the design of a large-scale complex networks model, and whose results support decision-making for adjusting the cost structure for the hydrocarbons distribution under a low-price scenario. Then, given the characteristics of the integer models, the simulation will be used to create scenarios. Several systems have been put together to represent the operation of the hydrocarbons transportation and collection system, using virtual routes without taking into account the real routes, the installed capacity, and economy of hydrocarbons. These efforts have been very

valuable and have enabled us to see the importance of having more precise tools that include economic aspects. This article is organized as follows: Section 2 briefly describes the problem and its main characteristics. Section 3 presents a state of the art where the models and methods employed in the relevant literature are reviewed, with attention being paid to optimization, optimization-simulation and simulation models. Section 4 shows the most relevant lines of research and analyzes the literature. Finally, we give our conclusions and suggestions for future research.

2. DESCRIPTION OF THE PROBLEM

The hydrocarbons distribution, collection, and treatment system consist of hundreds of pipelines and facilities of various types and capacities that make up a highly complex network that, through multiple routes, connects the production complexes with the points of sale.

This complexity is multiplied by this system being used to distribute several products of varied qualities that are mixed with each other to obtain new products while being transported through the network.

Another particularity of the network is that the nodes can be associated with different processes, some of which specifically relate to transport, such as compression for gases or pumping for liquids, and others for the conditioning of the products, such as dehydration, desalination, and mixing, to name but a few.

Both the economic information for each pipeline and the prices associated with the products are preponderant for the programming of the economy that is implicit in the distribution, collection, and treatment system.

The problem to be solved consists of finding the routes that optimize the distribution of hydrocarbons from the production complexes to the points of sale, maximizing expected profits and giving customer satisfaction in terms of the quantity and quality of the product, in other words, the mixture that reaches the points of sale must meet the required quality.

Every transfer node that receives production from two or more nodes must have a process module for obtaining the quality of the outlet mixture. Routes generally have several transfer nodes.

In this regard, the problem can be identified as a maximum distribution problem in a network with minimum costs and with the following characteristics and restrictions.

This is a multimodal network as it considers two products: oil and gas, as well as having three types of pipelines: oil pipelines, gas pipelines and oil and gas pipelines. The methods to be employed for finding a solution may consider every product in the multimodal network, or else break the network down into layers in accordance with each product.

This problem consists of maximizing the profits obtained from the sale of the hydrocarbons that circulate in the system while at the same time considering the minimum cost. Some authors describe this problem as one of maximum flow at minimum cost. A minimum-cost maximum flow for a $G = (V, E)$ network is a maximum

flow with the lowest possible cost. This problem combines the maximum flow (obtaining the highest possible flow from the source node (or nodes) to the sink node (or nodes), with the lowest cost path from the source to the sink node.

There are several source nodes and several sink nodes.

What goes into the transfer nodes is the same as what comes out, as long as they are not transferred nodes that deal with mixtures or processes, in which case the products leave the node improved and differentiated by quality and other characteristics.

The pipelines have an installed capacity that depends on their diameters, length, intake and outlet pressures, while also considering chemical factors that are inherent to the product.

Costs per section (pipelines) are considered as is the volume that flows. It is a large-scale network as it has more than 300 nodes and 500 arcs.

The following figure 1 shows a part of the network in simplified form.

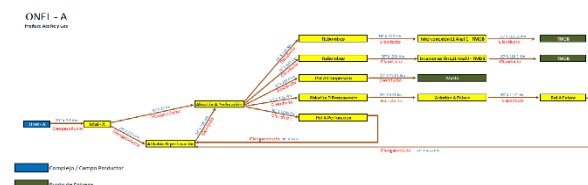


Fig.1 Simplified network of the problem

3. STATE OF THE ART

We will now review and describe a variety of articles published over the last few years. These articles are important for the definition of the models and tools to be used for solving the problem, however some of them were considered because of the problem's structure, such as a distribution network, even though in several of them the product is natural gas.

We will make a classification of the articles according to the type of problem being posed in the network or the approach for optimizing it, thus we get:

The products that go through chemical processes at certain nodes, as well as the characteristics inherent to said products.

Focus on the network's supply chain.

The above classification is framed around the models and their solution methods, which are basically optimization and simulation models.

The transport of hydrocarbons is a very important process for the oil and gas industry and, as such, needs to be performed with maximum efficiency. Pipeline systems are known to be the most economical, effective and safe means of transporting these products, but this literature review is required to support said assertion.

3.1. Optimization Models

Because of their relevance, since 2001 efforts have been made to optimize hydrocarbon transport networks. That

year, Jokic and Zavargo developed a nonlinear programming model (NLP) for optimizing a network for oil transport specified the volumes to be transported and considered the pressures at the intake and outlet from the pipelines, thus managing to minimize the operating cost. The model was solved using Mathead 2000 software.

Adeyanju and Oyekunle (2004) later developed a nonlinear optimization procedure NLP (objective function and nonlinear constraints), for a natural gas transportation network using an adaptation of the generalized reduced gradient algorithm, with which they determined the optimum economic conditions under which natural gas can be transported through a network of gas pipelines and compression stations.

MirHassani et al. (2008) presented an integer programming approach to oil derivative transportation scheduling. The system they reported is composed of an oil refinery, a multi-branch multi-product pipeline connected to several depots and local consumer markets that receive large quantities of refinery products. Batches of refined products and grades are pumped back-to-back in the pipeline, without any separation device between them. The sequence and length should be carefully selected for such pumping runs to meet market demands while, at the same time, satisfying a lot of pipeline operational constraints, such as minimum interfaces. The model was a MIP and was solved using CPLEX.

Selot (2009) analyzed short-term (2-12 weeks) supply chain management in upstream natural gas networks. A global optimization model (GO) is used for the production system, as it is a nonlinear mixed integer programming (MINLP) model. This paper included a model made up of two components: the infrastructure model, which is a physical model of the system (in other words, the wells, the pipelines and facilities) and the contractual model, which is a mathematical representation of the existing regulations.

It is important to explain the terms “upstream” and “downstream”:

"Upstream" and "downstream" are general business terms referring to oil or Gas Company's location in the supply chain. The closer to the end user a function or firm is, the further downstream it is said to be. Raw material extraction and production are elements of the supply chain considered to be upstream. Upstream companies identify oil and natural gas deposits and engage in the extraction of these resources from underground. These firms are often called exploration and production companies. Refiners represent the downstream element of the oil and gas supply chain.

Midstream operations link the upstream and downstream entities. Midstream operations mostly include resource

transportation and storage, such as pipelines and gathering systems.



Figure 2: Production and Gathering: Three Sectors
Source: <https://www.psgdover.com/en/oil-and-gas/oil-gas-market-overview/oil-gas-upstream>

Chebouba, et al. (2009) proposed a nonlinear integer model (NLIP) for which they designed an ant colony optimization algorithm for gas pipeline operations with a constant flow. This is a system consisting of connected compression stations. The decision variables are chosen to determine the number of turbochargers in operation and the discharge pressure for each compression station. The objective function is the power consumed by these stations in the system.

Analyzing the distribution of petroleum products in China, Huanchao et al. (2009) developed a logistics model for oil, based on the inventory-transportation integrated optimization problem - a linear problem (LP) using LINGO (Optimization Modeling Software for Linear, Nonlinear, and Integer Programming) software - to check and compare its results with traditional optimization methods and be able to prove its superiority. With the rise in global demand for energy, natural gas plays an increasingly important role in the energy market. To meet demand, optimization techniques, producing some promising results, have been widely used in the natural gas industry. In this vein Zheng et al. (2010) made a detailed analysis of optimization models in the natural gas industry, focusing on production, transport and the market. Thus, for the production problem, they proposed models for the production scheduling problem and the maximal recovery problem. For the gas transportation problem, the network design problems and the optimal fuel cost problem, and finally for the market problem, both regulated and deregulated market models are considered. The models used are nonlinear and non-convex so linearization is performed for their solution or the use of metaheuristics is proposed. Borraz-Sánchez (2010), in his doctoral dissertation, developed some models for solving the problem of optimizing gas pipelines. In this project, a multi-period model is proposed to tackle the *line-packing problem*. The model has nonlinear constraints and both continuous and integer decision variables, and qualities thus as such as a mixed-integer nonlinear programming (MINLP)

model. In the project, authors develop an extensive numerical experiment to evaluate the computability of the model. This experimental phase is based on a GAMS formulation for the MINLP model, while applying the global optimizer BARON. Exact methods and heuristics are used in the models that are presented.

Jin and Wojtanowicz (2010) developed a study aimed at optimizing the natural gas network to minimize its energy consumption and cost. They used four different optimization methods: the penalty function method; pattern search; implicit enumeration and non-sequential dynamic programming, to solve the problem. The results show that cost savings, because of global optimization, are reduced with increased throughput.

Domschke et al (2011) studied the technical optimization problem of a transient gas network, which can be considered a minimum-cost flow problem with a non-linear objective function and additional non-linear constraints on the network arcs. They solved it through a “combination of a novel mixed integer linear programming approach based on piecewise linearization and a classic sequential quadratic program applied for given combinatorial constraints”.

Gupta and Grossmann (2012) presented an efficient strategic/tactical planning model for the problem of the development of offshore oilfields, which is generic and can be extended to include other complexities. The model, which is multi-period and mixed integer non-linear programming MINLP, is proposed for multi-field sites and includes three components (oil, water and gas) explicitly in the formulation. Aimed at maximizing the present total net value for the long-term planning horizon, the model involves decisions relating to the installation of FPSO (Floating Production Storage and Offloading), well drilling schedules and rates of production for the three components in each period. This model can be effectively solved using DICOPT (DIScrete and COntinuous OPTimizer) developed by Grossman and is useful for real cases as it gives good quality solutions.

Hübner y Haubrich (2012) proposed a method based on genetic algorithms for planning and optimizing natural gas distribution networks from a long-term planning perspective. The method can calculate network structures that are cost-efficient in terms of all the technical and economic conditions.

Babonneau et al. (2012) developed a multi-objective model to get around the difficulty represented by the operation of gas distribution networks, because of the total energy dissipated in the network. The two objectives posed in the model correspond to the

investment cost function and the energy that is required to transport the gas.

Borraz-Sánchez and Haugland (2013) approached the flow maximization problem in a natural gas transportation pipeline system. Their model incorporates the variation in pipeline flow capacities with the specific gravity of the gas and compressibility. Given that the proposed model is not convex and, therefore the global optimization can take a long time, they propose for their solution a heuristic method based on an iterative approach where a simpler NLP model solved in each iteration.

MohamadiBaghmolaei et al. (2014) carried out a study for minimizing the fuel consumption of a pipeline system that includes reinforcement units. For the analysis they used the steady-state non-isothermal natural gas flow. Due to the lack of information and difficulties in predicting gas turbine and compressor efficiency, intelligent systems may be used to find the relations between the parameters involved, including the Artificial Neural Network (ANN), the Adaptive Neuro-Fuzzy Inference System (ANFIS) and the Fuzzy Inference System (FIS), for predicting and optimizing the pipeline network from the IGAT 5 system that transports the natural gas from Asalouyeh (South Pars Energy Zone-IRAN) in order to injected into the oil wells. The results showed that ANN is slightly more precise than the other two predictive methods. Therefore, the ANN results were introduced into a Genetic Algorithm (GA) to determine the optimum speed for each compressor and its compression ratio.

For their part, Alinia et al. (2014) proposed a multi-objective approach to finding the optimum operating conditions for a natural gas network. For this purpose, they made a thermodynamic model of natural gas through the main elements of the network. Their aim is to find the optimum values of three objective functions: i) the maximum gas delivery flow; ii) the line pack and iii) the minimum operating cost. Here, a fast and elitist non-dominated sorting genetic-algorithm (NSGA-II) is applied by considering fourteen decision variables: the number of running turbo-compressors (TCs) and their rotational speed in compressor stations as well as the gas flow rate and pressure at injection points. The results of multi-objective optimization are obtained as a set of multiple optimum solutions, called ‘the Pareto optimal solutions’. Furthermore, a set of typical constraints governing the pipeline operation is subjected to obtain more practical solutions.

Fabro et al. (2014) presented a model too assist in the operational decision-making of scheduling activities in a gas pipeline that transports heavy oil derivatives. The

approach they proposed develops a decomposition procedure that uses a sequence of mathematical and heuristic programming models (MILP), which were run on the CPLEX program to solve the problem.

Wu et al. (2014) built an MINLP optimization model for natural gas trunk pipelines for balancing the maximum operation benefit and the maximum transmission amount.

The sum of weight method was used to combine the two objective functions and, in this way, modeled a hybrid objective function. To weight each objective function, the Analytical Hierarchy Method (AHP) was used. Restrictions related to node pressure, flow rate and temperature were considered as restrictions of the model. The power and condition of the compressor, the pressure and temperature equations of the pipeline were also incorporated into the model. As the model is non-linear, the particle swarm optimization algorithm (PSO) was used to solve it, and the adaptive inertial weight adjustment method was adopted to improve the basic PSO for its premature defect. The IAPSO shows a faster convergence speed and better solution results than those of the other four PSO

Ribeiro de Lucerna et al. (2014) generated an optimization method for submarine pipeline routes, employed to carry the oil and gas from offshore platforms. Several methods associated with the modeling and solution of the optimization problem were addressed, including: the geometrical parameterization of the candidate routes; their encoding in the context of a genetic algorithm (GA) and the incorporation into the objective function of the several design criteria involved in the route evaluation.

Pfetsch et al. (2015) researched methods for solving gas transportation issues, particularly the validation of the nomination problem that takes as a given a gas transmission network consisting of passive pipelines, active, controllable elements and an amount of gas at every entry and exit point of the network; for which operational settings are sought for all the active elements in such a way that there is a network state that fulfills all the physical, technical, and legal constraints. The authors described a two-stage approach for solving the nonlinear feasibility problem; the first phase with four algorithms: the methods of mixed integer linear programming (MILP), mixed integer non-linear programming (MINLP), nonlinear reduced gradient (GRNL) and de complementarity constraints (CRP) for calculating the possible settings for discrete decisions; while the second phase employs a continuous nonlinear programming model of the gas network.

Chebouba (2015) addressed the management of the "GZ1 Hassi R'mell-Arzew" gas pipeline network. For this system, the decision-making on the line pack usually involves a delicate balance between the minimization of fuel consumption in the compression stations and the maximizing of the gas line pack. To select an acceptable pack considering these two aspects for the "GZ1 Hassi R'mell-Arzew" pipeline, the idea was introduced of multi-objective decision-making. The first step in the development of this procedure is the derivation of a numerical method to analyze the flow through the pipeline under transient isothermal conditions, for which the NSGA-II (Non-dominated Sorting Genetic Algorithm) algorithm of the mode FRONTIER (coupled with a Matlab program) was used to solve the multi-objective problem.

Kazemi et al. (2015) proposed a deterministic mixed integer linear programming (MILP) model for a downstream petroleum supply chain (PSC) network to determine the optimal distribution center (DC) locations, capacities, transportation modes, and transfer volumes. This model minimizes multi-echelon multi-product cost along the refineries, distribution centers, transportation modes and demand nodes.

Lui et al. (2015) analyzing the characteristics of oil-gas production process and the relationship between subsystems, a multi-objective optimization model is proposed with maximizing the overall oil production and minimizing the overall water production and comprehensive energy consumption for per-ton oil. And then the non-dominated sorting genetic algorithm-II (NSGA-II) is used to solve the model. To further improve the diversity and convergence of Pareto optimal solutions obtained by NSGA-II algorithm, an improved NSGA-II algorithm (I-NSGA-II) is proposed.

In recent years, a large amount of research has been conducted on problems in the natural gas industry and, specifically, in the optimization of the pipeline network. Ríos-Mercado and Borraz-Sánchez (2015) presented a review of the current state of the art. The authors focus on categories such as: short-term storage (line packing problems), gas quality satisfaction (grouping problems) and compressor station modeling (problems of fuel cost minimization). The optimization models were discussed, highlighting the modeling aspects and the most relevant solution approaches known to date.

Sedliak and Zácik (2016) designed a methodology for solving optimization tasks for gas transport in a pipeline system such as: finding of maximal outflow; minimization problems (e.g., finding minimal gas consumption under certain transport conditions), and multi-objective optimization (e.g., minimal energy consumption and prescribed line pack). To this end, they made modifications to the evolution strategy algorithm.

The proposed algorithm was implemented in C++ programming language as an embedded module in software MARTI Studio—a general tool for solving tasks in gas industry.

Zhou et al. (2017) described, in a document, the optimization problems of pipeline transport for multi-phase flows. This article established a route optimization model that combines the hydraulic calculations with optimization theory and adopt the general genetic algorithm (gGA) and the steady-state genetic algorithm (ssGA) for its solution. It also obtains the optimum route and discusses the influence of the parameters setting the result. This algorithm was applied to determining optimum pipeline routes in the methane collection and transportation system in the coal fields of Shanxi province, China. The result showed that the algorithm is feasible and improves the hydraulic properties by reducing the pressure drop along the line.

Zhang and Liu (2017) developed an optimal operation model based on an improved genetic algorithm for natural gas pipeline network. For its solution, they chose the maximum benefit and maximum flow as the objective function, and selected several conditions as the constraints including the input and output of gas, the input and output pressure of gas, the handling capacity of the compression station, the strength of the pipeline, the pressure drop in the pipeline, the compressor, the valve, and the flow balance of the node of the pipeline network. They also establish an optimal mathematical operation model for the natural gas pipeline network. For this, they propose an improved genetic algorithm as the possibility of the fitness value of an individual in the initial population is abnormal and the possibility of the probabilities of the crossover and the mutation are too high or too low.

Ye et al. (2017). They studied the programming and routing of the tramp shipment and the oil supply chain. With this objective they developed two models of whole programming (MILP) for the assignment between tasks, deposits and timing problems. The first model used a concept of a time interval in a continuous time representation, where they consider the limitations related to the allocation of vessels, capacity, time, demand and control of slack. The second model uses a discrete time representation with time allocation, portal count and inventory control restrictions.

The authors Zhang et al. (2017) developed a hybrid method for detailed programming of a pipeline with multiple pumping stations. They explain that a multi-product pipeline is the most effective way to transport refined products and is of vital importance in the energy supply chain. The essential task in the actual operation of

the pipeline is to schedule the delivery and injection of numerous types of products. The article presents a nonlinear mixed integer programming model (MINLP) for ducts with a single source and multiple pumping stations. The model contains two parts and is solved by a hybrid computational approach, the ant colony optimization algorithm (ACO) and the simplex (SM) method.

Yea et al. (2017) the refined oil transportation problem investigated in this paper lies on the intersection of the scheduling and routing of tramp shipping and the petroleum supply chain, with unprecedented large-scale and complex rules. Two mixed-integer linear programming formulations MILP are developed for the assignment between tasks, vessels, and timing issues. The first model uses a time-slot concept under a continuous-time representation, where the constraints that deal with vessel assignment, capacity, timing, demand, and slack stock control are considered. The second model uses a discrete-time representation with time assignment, portal counting, and strict stock control constraints. Finally, the impact of the model parameters is analyzed under different optimization scenarios.

Chen et al. (2017) explained how to optimize the detailed schedules of a multi-product pipeline. They presented a MILPD mixed discrete time linear integer programming model, through an objective function that consists of the minimum sum of the pump speed variations in each pipe segment along a pipeline during a planning horizon. In addition to operational limitations, two sets of special restrictions are introduced into the model to improve the operability and viability of detailed schedules. It was concluded that the more stable the pumping speed of a pipe segment, the lower the friction loss for the pumping products. The proposed MILP model is successfully tested in two real-world multiproduct pipelines using CPLEX.

Mikolajková et al. (2017) presented a model of a pipeline network for gas distribution considering supply of gas, either from external gas networks or as injected biogas or gasified liquefied natural gas (LNG) at terminals. The model is based on mass and energy balance equations for the network nodes, equations of the pressure drop of a compressible gas in the pipes, as well as expressions of gas compression in compressor nodes. The model is applied within an optimization framework where the optimal supply of natural gas to the customers is studied under a multi-period mixed integer nonlinear programming (MINLP) formulation, considering possible extensions of the pipeline network to new sites as well as potential supply of the gas from LNG terminals. The natural gas network in Finland is used in a case study, which determines the network's size and operation conditions.

Zhang et al. (2018) explained in their paper that the optimization of multi-product pipeline scheduling is complicated due to multi-batch sequent transportation and multi-point delivery. Based on this fact authors considered batch interface migration and divided the

model into time nodes sequencing issue and a mixed-integer linear programming (MILP) model with the known time node sequence. And a self-learning approach is proposed through the combination of fuzzy clustering analysis and ant colony optimization (ACO). This algorithm is capable of self-learning, which greatly improves the calculation speed and efficiency. At last, a real pipeline case in China is presented as an example to illustrate the reliability and practicability of the proposed model.

3.2. Optimization and Simulation

Aalto (2008) pointed out that many pipeline systems are nonlinear, such as compression station shutdown or start-up. A dynamic, receding horizon optimization problem was defined, where the free response prediction of the pipeline was obtained from a pipeline simulator and the optimal values of the decision variables were obtained by solving an approximate quadratic programming (QP) problem, where the cost function is the energy consumption of the compression stations. The problem was broadened using discrete decision variables to represent the compressors' shutdown/start-up commands. A mixed logical dynamical system was defined, but the resulting mixed-integer quadratic programming problem was shown to be very high dimensional. Whereas, a sequence of these types of problems was defined that resulted in an optimization problem with a considerably smaller dimension. The receding horizon optimization was tested in a simulation environment and comparison with data from a true natural gas pipeline shows 5 to 8 % savings in compressor energy consumption

Rizwan et al. (2013) presented an approach adopted by Kuwait Oil Company to establish an integrated Crude Oil Export Pipeline simulation model in South & East Kuwait area to achieve increase in overall asset-wide production and to improve future Pipeline & Facilities Design.

The simulation used As-Built pipeline data along with field data to achieve the objectives of the study.

Accuracy of the pipeline model was verified by comparing simulation results of the existing pipelines and manifolds with the operating data to confirm that model results duplicated field measurements. The model developed in this study has the characteristics and the ability to predict the flows and pressures under wide range of conditions — including various operational modes and constraints.

The model accurately predicted the capacities and raised few flags which were solved within short time and subsequently the network was optimized. Hydraulics study revealed that no additional capacity or looping were required. Model was studied for reliability of supply under wide range of conditions subject to potential bottlenecks and constraints which were identified in the study.

Huang et al. (2015) analyzed underground oil pipelines, which are made from pressurized pipes, where, if there is any damage, consequences could be disastrous. Oil pipeline accidents caused by stress can be attributed to material corrosion, impractical design, manufacturing defect, environmental damage, and man-made destruction. In this study, by using the stress analysis software, CAESAR II, pipeline stress was analyzed under the same operating conditions and different piping technologies. Comparing the different simulation consequences of each technology, an optimized laying process was proposed to reduce the stress of underground oil pipelines in steep areas. This article uses simulation and optimization.

3.3. Simulation Methods

Herrán-González et al. (2009) performed the modeling and simulation of a gas distribution pipeline network. Gas ducts are the most important components of such kind of systems since they define the major dynamic characteristics. Isothermal, unidirectional flow is usually assumed when modeling the gas flow through a gas duct. This paper presents two simplified models derived from the set of partial differential equations governing the dynamics of the process. These models include the inclination term, neglected in most related papers. Moreover, two numerical schemes are presented for the integration of such models. Also, it is shown how the pressure drop along the pipe has a strong dependency with the inclination term. To solve the system dynamics through the proposed numerical schemes a based MATLAB-Simulink library was built.

Behbahani-Nejad et al. (2010) developed an efficient transient flow simulation for pipelines and networks. The proposed transient flow simulation is based on the transfer function models and MATLAB-Simulink. The transfer functions equivalent to the non-linear control equations were derived for different types of boundary conditions. Subsequently, a MATLAB-Simulink library was developed and proposed considering any border conditions. To verify the accuracy and computational efficiency of the proposed simulation, the results obtained were compared with the finite difference schemes. In the simulation, the effect of the inertia of the flow was incorporated. Efficiency is shown through several instances and it is verified that the proposed simulation is sufficiently accurate and computationally more efficient than other methods.

Woldeyohannes and Majid (2011a) discussed the use of a simulation model to analyze the effect of the age of pipes on the performance of a natural gas transmission system. The flow equations which govern the simulation were modified to consider the effect of the age of pipes. They evaluated and compared the performance of three

groups of pipelines and the results of the simulation analysis showed a 2.16 and 4.35% drop in the flow capacity for 10 and 20-year-old pipes, respectively.

Woldeyohannes and Majid (2011b) developed a simulation model for the analysis of transmission pipeline network system (TPNS) with detailed characteristics of compressor stations. The compressor station is the key element in the TPNS as it provides energy to keep the gas moving. The simulation model is used to create a system that simulates TPNS with different configurations to get pressure and flow parameters. The mathematical formulations for the TPNS simulation were derived from the principles of flow of fluid through pipe, mass balance and compressor characteristics. To determine the unknown pressure and flow parameters, a visual C++ code was developed based on Newton–Raphson solution technique.

Cernelev et al. (2014) focused their research on the problem of identifying and removing bottlenecks in a multi-terminal oil and gas pipeline network while achieving quality and delivery targets, which is a very real and complex problem. The most effective way to meet the above business objective was to develop a terminal network simulation model. This paper is a case study describing the approach in designing a complex multi-nodal pipeline network simulation model aimed at resolving a critical inter-company storage problem for a major refiner.

Costa et al. (2014) explained that oil refining companies and distributors often use pipelines to transport their products. In highly integrated, geographically challenging contexts, this may result in complex logistical systems. Pipelines which transport multiple products connect tanks, forming a self-contained environment where distribution routes (called logistical channels), tactical inventory locations and operational criteria are defined to transfer, receive and deliver liquid oil derivatives. Authors describe a simulation model designed to represent such a regional pipeline network and includes a case study of a Brazilian region with refineries, a maritime terminal, a hub terminal and distribution bases.

Szoplík (2016) The objective of this study was to elaborate a relation between the pressure and the current of gas introduced in the gas network for which gas modeling results were used in the network, obtained for the existing gas network and with real data about the load of the network depending on the time of day and the air temperature, this author presents an example of application. Based on the results obtained, it was concluded that this approach allows reducing the amount of gas supplied to the network by 0.4% of the annual load.

Addo Pambour et al. (2016) This paper presents an integrated transient hydraulic model that describes the dynamic behavior of natural gas transport systems (GTS). The model includes sub models of the most

important facilities comprising a GTS, such as pipelines, compressor stations, pressure reduction stations, underground gas storage facilities and LNG Terminals. The sub models are combined to an integrated network model and the algorithm for solving the resulting system of equations is detailed.

Corbet et al. (2018) described a dynamic flow model in networks, designed to inform analyses of disruptions in infrastructures and to help in the formulation of policies to design robust mitigations. They conceptualized the adaptive responses of infrastructure networks to perturbations as market transactions and business decisions of operators by means of simulation. They approximated commodity flows in these networks by a diffusion equation, with nonlinearities introduced to model capacity limits.

4. LINES OF RESEARCH

This state of the art shows the two main areas of research into the solution of problems involved with natural gas networks and hydrocarbon networks, in general. About optimization, models have been identified that, in their majority, are Mixed Integer Non-Linear Programming and the solution methods can be exact, using software such as CPLEX, among others, and heuristic methods particularly genetic, neural network and ant colony algorithms. The model varies depending on what the objective of the optimization is. Some articles only mention network optimization in respect of whether the flow being transported is gas or oil. Other articles consider the power, energy and fuel that are being consumed, either as the aim or as constraints of the model. Articles were also found that seek to optimize inventory and transport and production costs.

Another important characteristic is the focus, whether a supply chain, a scheduling and routing problem, maintenance and safeguarding problems or network design is being considered.

Some authors have approached the hydrocarbons transport network problem in general and use optimization and simulation where a short, medium and long-term planning horizon is realistically considered, and the infrastructure and its useful age are considered.

As for simulation, the literature is not quite so abundant. However, we found results that, just like the authors that used optimization and simulation, consider infrastructure, the market and major planning horizons. By using simulation, the idea that the problem is stochastic is taken as a given, which enables us to have an analytical tool that can act as a support for the optimization techniques.

5. CONCLUSIONS

The review of these articles shows that the problem, in general, of optimizing the management of hydrocarbons in a pipeline network is fundamental while the network's resilience and vulnerability are important factors whose

consideration should be included in future phases of the project.

A first phase consisted of reviewing and analyzing the articles published over the last few years on the subject. On this basis, the decision is made about which are the essential pieces for the development of the methodology, models and solution methods for solving the optimal routing problem. Afterwards more factors in the network are considered, such as the production processes, blends and market. Another aspect that we believe is important is sustainability, resilience and environmental impact.

Given the characteristics of PEMEX's hydrocarbons network, it is important to have analytical tools like simulation and optimization tools where different models can be constructed for solving linear integer and nonlinear integer and continuous problems.

Finally, it is important to consider the validation of the models and results that are obtained, together with their publication in international scientific media.

ACKNOWLEDGEMENTS

To PAPIIT project IT102117 DGAPA-UNAM.

REFERENCES

- Jokic A., Zavargo Z. 2001. Optimization of pipeline network for oil transport. Article in Hungarian Journal of Industrial Chemistry 29(2):113-117.
- Adeyanju O.A., Oyekunle L.O. 2004. Optimization of Gas Natural Transportation in Pipeline. Petroleum and Gas Engineering Programme. Petroleum and Gas Engineering Programme, Department of Chemical Engineering, University of Lagos. Nigeria.
- MirHassani S.A., Ghorbanalizadeh M. 2008. The multi-product pipeline scheduling system. Computers and Mathematics with Applications 56, 891-897.
- Selot A. 2009. Short-Term Supply Chain Management in Upstream Natural Gas Systems. Thesis (PhD), Department of Chemical Engineering, Massachusetts Institute of Technology.
- Chebouba A., Yalaoui F., Smati A., Amodeo L., Younsi K., Tairi A. 2009. Optimization of natural gas pipeline transportation using ant colony optimization. Computers and Operations Research, 36(6):1916-23.
- Huanchao T., Lixin T., Lin J. 2009. Inventory-Transportation Integrated Optimization Problem: A Model of Product Oil Logistics. International Journal of Nonlinear Science, 1, 92-96.
- Zheng QP., Rebennack S., Iliadis NA, Pardalos PM. 2010. Optimization Models in the Natural Gas Industry. Chapter in the Handbook of Power Systems I, 121-148. Rebennack, S., Pardalos, P.M., Pereira, M.V.F., Iliadis, N.A. Eds., Springer Verlag.
- Borraz-Sánchez C. 2010. Optimization Methods for Pipeline Transportation of Gas Natural. Department of Informatics. Thesis (PhD). University of Bergen, Norway.
- Jin L., A. K. Wojtanowicz. 2010. Optimization on large gas pipeline network. A case study in China. Journal of Canadian Petroleum Technology, 49 (4):36-43.
- Domschke P., Geißler B., Kolb O., Lang J., Martin A., Morsi A. 2011. Combination of Nonlinear and Linear Optimization of Transient Gas Networks. INFORMS Journal on Computing, 605-617.
- Gupta V., Grossmann I. 2012. An Efficient Multiperiod MINLP Model for Optimal Planning of Offshore Oil and Gas Field Infrastructure. Department of Chemical Engineering, Carnegie Mellon University Pittsburgh. Ind. Eng. Chem. Res., 51 (19): 6823-6840
- Hübner M, Haubrich H-J. 2012. Long-term pressure-stage comprehensive planning of natural gas networks. In: Sorokin A, Rebennack S, Pardalos PM, Iliadis NA, Pereira MVF, editors. Handbook of networks in power systems II. Energy systems. Berlin Heidelberg: Springer, 37-59.
- Babonneau F, Nesterov Y, Vial J.P. 2012. Design and operations of gas transmission networks. Operations Research 60(1):34-47.
- Borraz-Sánchez C, Haugland D. 2013. Optimization methods for pipeline transportation of natural gas with variable specific gravity and compressibility. TOP, 21(3):524-41.
- MohamadiBaghmolaei M, Mahmoudy M, Jafari D, MohamadiBaghmolaei R, Tabkhi F. 2014. Assessing and optimization of pipeline system performance using intelligent systems. J Natural Gas Sci Eng., 18:64-76.
- Alinia Kashani AH, Molaei R. 2014. Techno-economical and environmental optimization of natural gas network operation. Chem Eng Res Des, 92 (11):2106-22.
- Fabro J., Stebel S., Rossato D., Polli H., Arruda L.V.R., Neves F., Ribas P., Barbosa-Póvoa A., Relvas S. A., 2014. MILP (mixed Integer Linear Programming) decomposition solution to the scheduling of heavy oil derivatives in a real-world pipeline. Computers and Chemical Engineering, 66 (4): 124-138.
- Wu X, Li C, Jia W, He Y. 2014. Optimal operation of trunk natural gas pipelines via an inertia-adaptive particle swarm optimization algorithm. J Natural Gas Sci Eng., 21 (9):10.
- Ribeiro de Lucerna R., Souza Baioco J., Souza Leite Pires de Lima B., Horst Albrecht C., Pinheiro Jacob B. 2014. Optimal design of submarine pipeline routes by genetic algorithm with different constraint handling techniques. Advances in Engineering Software, 76: 110-124.
- Pfetsch ME, Fügenschuh A, Geißler B, Geißler N, Gollmer R, Hiller B. 2015. Validation of nominations in gas network optimization: models, methods, and solutions. Optim Methods Softw., 30(1):15-53.

- Chebouba A. 2015. Multi objective optimization of line pack management of gas pipeline system. *Journal of Physics: Conference Series* 574 012114
- Kazemi Y., Szmerekovsky J. 2015. Modeling downstream petroleum supply chain: The importance of multi-mode transportation to strategic planning. *Transportation Research Part E* 83, 111–125.
- Liu T., Xianwen G., Wang L. 2015. Multi-objective optimization method using an improved NSGA-II algorithm for oil-gas production process. *Journal of the Taiwan Institute of Chemical Engineers*, 57, 42–53.
- Ríos-Mercado R., Borraz-Sánchez C. 2015. Optimization Problems in Natural Gas Transportation Systems: A state-of-the-art review. *Applied Energy*, 147, 536–555.
- Sedliak A., Zácik T. 2016. *Tatra Mountains Mathematical Publications*, 66 (1), 103–120.
- Zhou J., Liang G., Deng T., Gong J. 2017. Route Optimization of Pipeline in Gas-Liquid Two-Phase Flow Based on Genetic Algorithm. *International Journal of Chemical Engineering*. Article ID 1640303, 9 pages, Hindawi.
- Zhang Z., Liu X. 2017. Study on optimal operation of natural gas pipeline network based on improved genetic algorithm. *Advances in Mechanical Engineering*, 9(8):1–8.
- Ye Y., Shengming L., Yushan Z. 2017. A mixed-integer linear programming-based scheduling model for refined-oil shipping. *Computers and Chemical Engineering*, 99, 106–116.
- Zhang H., Liang Y., Liao Q., Wu M., Yan X. 2017. A hybrid computational approach for detailed scheduling of products in a pipeline with multiple pump stations. *Energy* 119, 612–628.
- Yea Y., Lianga S., Zhua Y. 2017. A mixed-integer linear programming-based scheduling model for refined-oil shipping *Computers and Chemical Engineering*, 99, 106–116
- Chen H., Zuo L., Wu Ch., Wang L., Diao F., Chen J., Huang Y. 2017. Optimizing detailed schedules of a multiproduct pipeline by a monolithic MILP formulation *Journal of Petroleum Science and Engineering*, 159, 148–163
- Mikolajková M., Haikarainen C., Saxén H., Pettersson F. 2017. Optimization of a natural gas distribution network with potential future extensions. *Energy*, 125, 848–859
- Zhang H., Liang Y., Liao Q., Shen Y., Yan, X. 2018. A self-learning approach for optimal detailed scheduling of multi-product pipeline. *Journal of Computational and Applied Mathematics*, 327, 41–63.
- Aalto H. 2008. *Optimal Control of Natural Gas Pipeline Networks: A Real-Time, Model-Based, Receding Horizon Optimisation Approach*. VDM Verlag, Saarbrücken Alemania.
- Rizwan M., Al-Otaibi M., Al-Khaledi S. 2013. *Crude Oil Network Modeling, Simulation and Optimization: Novel Approach and Operational Benefits*. Paper No. IOGPC2013-9853, pp. V001T02A007; 4 pages. ASME India Oil and Gas Pipeline Conference.
- Huang K., Wu J., Hu M., Xiang H., Zhang Z. 2015. Optimization and Stress Analysis of Underground Oil Pipelines in High and Steep Slope Areas. *The Open Civil Engineering Journal*, 9, 477–483.
- Herrán-González A., De La Cruz J.M., De Andrés-Toro B., Risco-Martín J.L. 2009. Modeling and simulation of a gas distribution pipeline network. *Applied Mathematical Modeling*, 33(3):1584–600.
- Behbahani-Nejad M., Bagheri A. 2010. The accuracy and efficiency of a MATLAB-Simulink library for transient flow simulation of gas pipelines and networks. *Journal of Petroleum Science and Engineering*, 70, 256–265.
- Woldeyohannes AD, Majid MAA. 2011a. Effect of Age of Pipes on Performance of Natural Gas Transmission Pipeline Network System. *Journal of Applied Sciences*, 11 (9): 1612–1617.
- Woldeyohannes AD, Majid MAA. 2011b. Simulation model for natural gas transmission pipeline network system. *Simul Model Pract Theory*, 19(1):196–212.
- Cernelev D., Chegus A., Lin F. 2014. Application of Multi-Nodal Network Simulation Models in The Debottlenecking of a Complex Pipeline Network. *Proceedings of the Winter Simulation Conference A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.*
- Costa R., Freitas A. Araujo C., Limoeiro C., Fuller D. 2014. Simulation model for regional oil derivatives pipeline networks considering batch scheduling and restricted storage capacity. *Proceedings of the Winter Simulation Conference A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.*
- Szoplík J. 2016. Improving the natural gas transporting based on the steady state simulation results. *Energy*, 109, 105–116
- Addo Pambour K., Bolado-Lavin R., Dijkema G. 2016. An integrated transient model for simulating the operation of natural gas transport systems. *Journal of Natural Gas Science and Engineering*, 28, 672–690
- Corbet T., Beyeler W., Wilson M., Flanagan T. 2018. A model for simulating adaptive, dynamic flows on networks: application to petroleum infrastructure. *Reliability Engineering and System Safety*, 169, 451–465.