The Refined Products Distribution Problem via Pipeline Systems: A Survey

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Abstract

The system configuration reported in most articles addressing the distribution of refined products using pipelines includes a refinery producing a number of oil derivatives, a set of market zones to which these products are delivered, and a single unidirectional flow pipeline connecting the refinery and the market zones. Larger and more realistic system configurations should include several refineries and a network of pipelines capable of dealing with reversible flows. This improvement in the ability of the model to represent the system comes with a high challenging degree of computational complexity. Furthermore, different measures of effectiveness may be considered as the objective function of the model, depending on the size of the system and nature of the operation. The main purpose of this article is to perform an extensive and systematic literature review for the problem to arrive at a taxonomy of the research work conducted in this area. The proposed classification considers modeling and solution approaches, optimization criteria, and the system configuration assumed in the reviewed approaches. Research perspectives and future research directions on this problem are proposed.

Keywords
Refined products distribution problem, multiproduct pipeline systems optimization,

1. Introduction

The distribution of refined products using pipeline systems has posed an increasingly significant challenge in the Operations Research (OR) community during the last two decades. The growing demand of petroleum products on a worldwide basis and the proliferation of new refined products, such as biofuels, have contributed to the complexity of the problem. As a result, in the last 20 years, a significant effort has been made to formulate a diversity of models and develop a wide range of analytical solution procedures, many of which being published in both refereed journals and conference proceedings from a strategic and planning perspective, being the latter the most investigated scenario. In virtually every publication in this field, a review of the most relevant related work is presented; nonetheless, in a vast majority of the cases, only a brief description of the corresponding methodologies is provided. Just in a few cases a more comprehensive perspective of the research contributions is presented. An example of this kind of discussion is found in reference [1].

Quite often technical literature reviews intended to focus on the main problem of pipeline-distribution of refined products, include important topics but only tangentially related to the problem. This may be the result of few available previous references in this relatively-new research area. These not-centrally related topics include, among
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others, planning and scheduling in petroleum refineries; crude oil scheduling in ports, refineries and pipelines; and the allocation of crude oil to tanks [2]. In the chemical industry, some reviews focus on the logistics of sulfuric acid production and distribution [3]. A comprehensive literature review of OR methodologies developed exclusively for the distribution of refined products by means of pipelines systems is currently needed. Such a survey would contribute to consolidate this field as an import ant OR topic.

Although there is an increasing number of studies aimed at reviewing relevant related work, still there remains the need of a systematic comprehensive review of the technical O.R. literature that will help both researchers and practitioners to identify solution methodologies for specific configurations and assumptions in a pipeline distribution system. Perhaps, more important, such reviews can provide a foundation to direct future research efforts. The aim of this paper is to present a systematic literature review of relevant publications in the field of distribution of refined products via pipelines. Two main elements addressed in the literature review are research perspectives and the taxonomy of research work. Some directions for future research work are proposed.

The main goals of this literature review are:

1. To determine the extent of the theory and research that have been developed in the field of refined product distribution via pipelines.
2. To identify the definition of concepts and measures which have already been established in the relevant technical literature and examine the research formulations and solution procedures.
3. To document what is known and what remains to be further explored in the field (research perspectives).
4. To become aware of difficulties experienced by other authors.
5. To classify the research work selected for this study.

The body of this paper is organized in six sections including this introduction. Section 2 describes the methodology of the literature review. Section 3 presents a summary of the research perspectives. Section 4 provides the proposed taxonomy for the research work in this area. Section 5 proposes future research directions. Section 6 summarizes the conclusions of the paper.

2. Methodology

A literature review is a written approach to examining published information on a particular topic or field. An author uses this review of literature to create a foundation and justification for his or her research or to demonstrate knowledge on the current state of a field.

The literature review presented in this paper is focused on research outcomes and methods, its goal is to identify central issues of the area of interest, providing a neutral representation of the material following a chronological format. This survey seeks to be an exhaustive review focused on journal articles documenting mathematical approaches to model and solve the problem of interest, following guidelines recommended in reference [4]. To properly describe the overall methodology followed to select, review, and classify the work documented in these references we will consider the following four key elements:

- Scope
- Selection
- Discussion
- Analysis

2.1 Scope of Survey

Despite the fact that the pipeline distribution of refined products is a problem of major economic importance, to the best of our knowledge, little attention has been paid to survey currently available research work based on mathematical formulations and analytical solution procedures. Research perspectives that provide guidelines and direction for future work are discussed. Following suggestions by Gall, Borg and Gall [5], this study will delimit research problems, summarize methodological insights, and provide recommendations for further research work.

2.2 Selection of Reviewed Articles

The bibliographical references selected for this review were chosen following two steps, based on the methodology proposed in reference [4]. The first step is an electronic search of academic databases. The second step involves
searching of specific articles retrieved in the first step, determining which of them seemed to be relevant, finding the bibliographical references of these articles, and repeating this process until a point of saturation is reached. Inclusion and exclusion criteria were defined to decide whether a bibliographical reference (article) would be included in the study or not. Despite the pioneering work of Hane and Ratliff [6] which addressed the problem from a strategic point of view in 1994, to the best of our knowledge little or no attention was paid to this problem at an operational level before year 2000 using mathematical models and exact solution methods. As a result, only journal articles published after the year 2000 were included in this study. Furthermore, only references documenting mathematical models and analytical solution procedures for systems using distribution pipelines at an operational level were included.

2.3 Discussion of Bibliographical References
For every selected paper, the system configuration is described, the objective function or measure of effectiveness is discussed, the size of the application of the problem is presented, the proposed mathematical model is classified into one of several types, and the solution procedure is briefly outlined.

2.4 Analysis and Interpretation
Future research directions in this field are identified based on significant challenges to extend the state-of-the-art of the problem under consideration. By necessity, due to the dynamic nature of the problem, this paper provides only partial results.

3. Research Perspectives

3.1 The System Investigated
For an important number of publications, the system under consideration is composed of a refinery, a set of depots serving the product demands in nearby market zones, a single pipeline connecting the refinery with the depots and a set of products to be distributed. This is the case of references [1–3] and [6–8] where the system consists of a refinery, five market zones, four products and a single pipeline connecting the market zones, depots or tank farms with the refinery. All these references use the same system topology or configuration to study different mathematical approaches. Similar topologies were studied in reference [10] with four depots. In references [10, 11] several configurations were studied, ranging from two depots to six depots for one refinery. An smaller system consisting of one refinery, one depot and six products is studied in references [11–13].

Alternative topologies have also been studied. For example, a system to distribute multiple refined products with a single pipeline connecting a refinery and a harbor is considered in references [14, 15]. More recently, networks of pipeline systems have also been investigated. For example, references [17, 18] consider a small system consisting of four unidirectional pipelines connecting two oil refineries, two dual-purpose terminals that either pump batches to meet downstream product requirements or receive material into their storage tanks, and two terminal points.

3.2 The Measure of Effectiveness
A classification of the objective functions or measures of effectiveness is needed to recognize the significant diversity of optimization criteria reported in the literature for this problem. The measure of effectiveness can be either economical or operational. The economical measure of effectiveness, which has received most of the attention, includes linear functions for pumping costs, transition costs, and inventory costs [2, 3, 6, 7, 17] and nonlinear functions as well [1]. In addition to these costs, in reference [21], a linear cost for starting and stopping each polyduct is included; also in reference [22] a linear backorder costs is included. Other costs have also received significant attention, such as the cost of backorders being tardily delivered to their destinations, and the cost of underutilizing the pipeline transportation capacity [8, 14, 17]. In some studies, a combination of the costs mentioned to this point has been studied; for example in reference [23], a weighted sum of the pumping and transition costs is considered. In references [10, 23] the objective function is composed of the pumping costs, the interface costs and the backorder costs. In more recent papers, where other topologies for the system have been addressed, new costs have been included in the objective function. For example, reference [24] considers a system topology consisting of two refineries, one single pipeline with reverse flow capabilities and a single terminal; besides pumping, inventory, interface and backordering costs, flow reversal and peak hour electricity costs are included in the objective function.
Among the operational measures of effectiveness, the most favored optimization criteria include the minimization of tank changeovers [16], the minimization of the total deviation of the actual delivering-operation time windows from due time windows of each type of product at each delivery station [10], and the minimization between total inputs and total outputs, the maximization of total pumping time and the maximization of the inventory level of the product with lowest capacity used at the end of the time horizon, all in a single objective function with weights assigned for each term [25]. Other studies have included aspects such as the minimization of the number of interfaces [26] and the number of tanks involved to receive and send products [17]. Also, the minimization of the violations to the lower and upper bounds on time to send or receive product was considered in reference [27].

4. The Taxonomy of the Research Work in This Field

4.1. Basic Terminology

In order to present the proposed classification of the research work in this field, it is important to first define some basic notation to identify the topology of the application considered in each of the journal articles included in the survey. This notation; which characterizes the main aspects of the system configuration or topology, was first introduced in reference [28] and it is based on the different types of applications documented in the currently available technical literature. The notation includes the following features: the number of sources, represented by $S$, the number of destinations, represented by $D$, the number of products, represented by $P$, and the type of flow, represented by $F$. Flow can be either reversible or not reversible. The symbol $u$ indicates unidirectional flow, and the symbol $b$ stands for bidirectional flow. The type of pipeline configuration is represented by the symbol $\pi$; which can be either a single pipeline, represented by $s$, or a network of pipelines, represented by $n$. The collective notation for the topology of a family of configurations for the problem under consideration is: $S/D/P/F/\pi$.

Table 1 provides additional conventions for the different elements of the optimization criteria reported in the references included in this survey as well as the corresponding convention to identify them; which includes acronyms and numbers. The purpose of these conventions is to use them in Table 2 to facilitate the presentation of the proposed taxonomy of the research work surveyed in this paper. Two acronyms are included to identify the solution procedures found in the literature and the different components of the measures of effectiveness reported by the bibliographical references included in this survey are identified by numbers.

<table>
<thead>
<tr>
<th>Meaning</th>
<th>Convention</th>
<th>Meaning</th>
<th>Convention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of Products Transported</td>
<td>1</td>
<td>Solver Default Settings</td>
<td>SDS</td>
</tr>
<tr>
<td>APT minus Products Delivered</td>
<td>2</td>
<td>Start/Stop cost of a polyduct</td>
<td>12</td>
</tr>
<tr>
<td>Backordering Costs</td>
<td>3</td>
<td>Tank Changeovers</td>
<td>13</td>
</tr>
<tr>
<td>Decomposition Structure</td>
<td>DS</td>
<td>Time Horizon</td>
<td>14</td>
</tr>
<tr>
<td>Flow Reversal Costs</td>
<td>5</td>
<td>Time Window Deviation</td>
<td>15</td>
</tr>
<tr>
<td>Heuristic Procedure</td>
<td>6</td>
<td>Total Final Inventory</td>
<td>16</td>
</tr>
<tr>
<td>Inventory Costs</td>
<td>7</td>
<td>Total Pumping Time</td>
<td>17</td>
</tr>
<tr>
<td>Number of Interfaces</td>
<td>8</td>
<td>Transition Costs</td>
<td>18</td>
</tr>
<tr>
<td>Peak Hour PMPC</td>
<td>9</td>
<td>Underutilization Costs</td>
<td>19</td>
</tr>
<tr>
<td>Pumping Costs</td>
<td>10</td>
<td>Reverse Flow Costs</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 2 provides the taxonomy of the selected references, corresponding to journal articles reporting on mathematical models and solution procedures only. This taxonomy was motivated by the several system configurations assumed in the selected bibliographical references. The table is composed by five column corresponding to Instance Topology, References, Mathematical Approaches, Objective Function and Solution Procedure. The column for Instance Topology provides the different configurations of the system that have been investigated. The entries of the column under the References heading identifies the journal articles that studied the corresponding topology reported in the previous column while the Mathematical Approach column presents the type
of mathematical model proposed for the topologies on the first column. The Objective Function column identifies what measures of effectiveness were studied for the topologies of the first column and the last column, Solution Procedure, reports on the solution strategy implemented to solve the proposed models.

Table 2: Taxonomy of the Research Work in Distribution of Refined Products using Pipeline Systems

<table>
<thead>
<tr>
<th>Instance Topology</th>
<th>References</th>
<th>Mathematical Approach</th>
<th>Objective Function</th>
<th>Solution Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1/8/u/s</td>
<td>[16]</td>
<td>MILP</td>
<td>13</td>
<td>SDS</td>
</tr>
<tr>
<td>1/1/6/u/s</td>
<td>[12, 24]</td>
<td>MILP</td>
<td>1, 16</td>
<td>SDS</td>
</tr>
<tr>
<td>1/1/6/u/s</td>
<td>[14]</td>
<td>MILP</td>
<td>2, 17</td>
<td>SDS</td>
</tr>
<tr>
<td>1/1/6/u/s</td>
<td>[15]</td>
<td>MILP</td>
<td>3, 7, 18, 19</td>
<td>SDS</td>
</tr>
<tr>
<td>1/3/4/u/n</td>
<td>[18, 25, 28]</td>
<td>MILP</td>
<td>3, 7, 8, 9, 10, 18, 19</td>
<td>SDS</td>
</tr>
<tr>
<td>1/5/3/u/s</td>
<td>[10]</td>
<td>MINLP</td>
<td>15</td>
<td>HP</td>
</tr>
<tr>
<td>1/5/4/u/s</td>
<td>[1–3], [6–8]</td>
<td>MILP, MINLP</td>
<td>7, 10, 18</td>
<td>SDS</td>
</tr>
<tr>
<td>2/2/5/u/n</td>
<td>[19]</td>
<td>MILP</td>
<td>3, 10, 14</td>
<td>SDS</td>
</tr>
<tr>
<td>2/2/8/b/s</td>
<td>[24]</td>
<td>MILP</td>
<td>3, 7, 9, 10, 18</td>
<td>SDS</td>
</tr>
<tr>
<td>2/3/3/u/s</td>
<td>[17, 28]</td>
<td>MILP</td>
<td>3, 18, 19</td>
<td>SDS</td>
</tr>
<tr>
<td>4/6/15/b/n</td>
<td>[27]</td>
<td>MILP</td>
<td>15</td>
<td>SDS</td>
</tr>
<tr>
<td>2/3/4/u/n</td>
<td>[21]</td>
<td>MILP</td>
<td>7, 10, 12, 18</td>
<td>SDS</td>
</tr>
<tr>
<td>2/3/5/u/s</td>
<td>[32]</td>
<td>MILP</td>
<td>3, 10, 18</td>
<td>SDS</td>
</tr>
<tr>
<td>2/9/4/u/n</td>
<td>[22]</td>
<td>MILP</td>
<td>3, 7, 10,18</td>
<td>SDS</td>
</tr>
</tbody>
</table>

Most of the research work undertaken for this problem has focused on the development of modeling approaches capable of dealing with the different system topologies that have been addressed and little attention has been paid to developing mathematical solution procedures for those models. A significant amount of references focused on a configuration consisting of one refinery, five market zones, four products and a single unidirectional pipeline for which MILP and MINLP models were developed to minimize pumping, transition and inventory costs. More recently, other system topologies, such as networks of pipelines with reverse flow capabilities, including several refineries, various market zones and dual purpose depots, have been studied.

Even though the most frequently used mathematical model was the Mixed Integer Linear Program (MILP), some bibliographical references formulated Mixed Integer Non Linear Program (MINLP) models to address different system topologies considering alternative optimization criteria.

5. Research Directions for Future Work in This Field

The review of the papers selected for this study revealed an interesting spectrum of research avenues posed by the problem under consideration. There are two main directions for future research: one concerns the nature of the model and the other concerns the solution strategy for the model, which is strongly related to the worth of the solution as a decision-making tool in a realistic application. For example, in reference [1], accounting for time-dependent unit pumping costs and solving the model with global optimization techniques (the proposed model in this reference is nonlinear) are two issues that should be addressed in future research efforts in this field. As a second example, several issues related to proposed future research work were identified by the authors of reference [17], including the addition of several features for the model and the corresponding solution procedure. One last example can be found in reference [10] where efforts are made to derive a better (more effective) solution procedure for the proposed model.

5.1 Future Research Related to the Nature of the Model

Reference [3] states that a major challenge is to monitor product content in the pipeline, subject to intermittent operation. Based on this, although not explicitly stated in that reference, it can be inferred that future models should...
include constraints to fulfill this need. In reference [8], the authors identified the contamination of the products inside the pipeline segments as one of the major concerns of the problem. The authors also claimed it is necessary to take into account hydraulic considerations such as friction and potential losses along the pipeline extension and the enormous amount of energy consumed by the booster stations.

In reference [14], the authors proposed the development of a new model extension to account for inventory management at the tank farm; this is made possible by disaggregating the tank farms and studying the tanks individually.

Reference [27] addressed time window constraints. The article recommends that the time window limits should be previously estimated by the assignment block. A second issue to be addressed would be the use of constraints to deal with work shifts to prevent pumping from starting in between the time periods while workers are changing their shifts.

In reference [31], the authors identify as their future work the overcoming of the model limitation of having a single batch of a particular product on the same pipeline segment and testing other objective functions. In reference [21], the generalization of the proposed model to deal with multilevel tree structure pipeline networks, where mainline branches are connected to final depots and lower level delivering lines, was identified as a topic receiving the future attention of the authors. Reference [20] identifies the necessity of the use of stochastic models due to the uncertainty about future demand of petroleum products and all the logistics related implications. Reference [10] recommends to include features such as adding depot capacity constraints and batch optimization of pipeline into the optimal model of scheduling.

Reference [23] argues that future research avenues for this problem should aim at including additional features of a real life scenario, such as peak hour pumping, pipeline direction reversals and stoppages. Reference [25] proposes to test the model under other system’s settings in order to assess its robustness and the inclusion of inventory management of the tanks, rather than using aggregated capacity. Increasing the level of detail of the proposed model is also part of their future research interests in this area. The authors of reference [24] are interested in generalizing the proposed formulation in this reference to deal with the operational planning of mesh-structure pipeline networks, including reversible and non-reversible segments.

5.2 Future Research Related to the Solution Procedure for the Model
In reference [8], the authors identified the contamination of the products inside the pipeline segments as one of the major concerns of the problem, along with the poor computational performance of the solution procedure. They also recommend the use of special decomposition techniques for solving larger instances of the proposed model due to the computational complexity. Decomposition strategies are also recommended in reference [13] in order to build a more robust solution procedure, not only considering a temporal decomposition but also by looking into the spatial dimension.

Due to the computational complexity of some of the proposed models, heuristic and metaheuristic procedures are also recommended, for example in reference [14], the development of heuristic procedures providing a set of favorable product sequences prior the model run to reduce model complexity was also proposed as a direction for future research work. The computational complexity associated with the solution process of the proposed model in reference [21] is identified by its authors as one issue to be addressed in future works by the implementation of several metaheuristic techniques to solve the problem. Reference [23] states the view that future research avenues for this problem should aim for obtaining better quality solutions in an acceptable computational time for larger pipeline networks.

6. Conclusions
New modeling approaches are required to better represent this system due to its inherent complexity and the striking features of its operation. In a vast majority of references, new modeling features are identified as future research avenues. In contrast, the solution procedure has received a little attention on the surveyed journal articles and perhaps less in the future research directions for this field, perhaps because the field is relatively new and the modeling approaches are still being explored. In summary, as stated in reference [13] combinatorial complexity vs. model level of rigorousness might become the focus of future studies in this field.
Outstanding features of the problem might also be receiving significant attention from the community, such as those listed in reference [23]: peak hour pumping, pipeline direction reversals and stoppages. These features pose the challenge of increasingly complex and large mathematical models, and certainly reflect the importance that this subject is gaining in current discussions about the oil industry, from which the Operations Research and Industrial Engineering community cannot be disconnected.

References