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A multiproduct gasoline supply chain with product standardization and postponement strategy

Rafael Bernardo Carmona Benítez[1], Héctor Cruz[2]

Universidad Anáhuac México

The supply chain problem studied in this paper arises from the analysis of the 2013 Mexican Energy Constitutional Reform, because this reform proposes a supply chain of gasoline that obligates the state-owned company to share its pipelines and storage terminals with private companies with the goal of lowering gasoline prices to consumers by enhancing competition. However, in this paper, it is proved that a supply chain problem is created when multiple oil companies share pipelines and storage terminals to simultaneously distribute different types of gasoline because operation costs are increased. In this paper, a multi-product gasoline supply chain is designed to solve this problem. This supply chain of gasoline allows multiple oil companies share pipelines and storage terminals to simultaneously distribute different types of gasoline minimizing costs. This supply chain of gasoline is designed based in the supply chain principle of collaboration, and in the supply chain strategies of product standardization and postponement. A multi-product pipeline inventory-transport problem with stochastic demand and variable lead time is developed (Mixed-Integer Nonlinear Programming Problem, MINLP), together with its global solution methodology, to optimize supply chains of gasoline. A small part of Mexico oil pipeline is used as study case. The main results are: the supply chain of gasoline proposed in the 2013 Mexican Energy Constitutional Reform is inviable because cost increase rather than decrease; and the supply chain of gasoline designed in this paper allows multiple oil companies share pipelines and storage terminals to simultaneously distribute different types of gasoline at minimum costs, as the 2013 Mexican Energy Constitutional Reform dictates.

1. Introduction

The development of the global economy is highly dependent on energy (Chen & Wu, 2017). The energy sector is formed by the fossil fuel industries, the electric power industry, the nuclear power industry, and the renewable energy industry. The oil industry is one of the fossil fuel industries with fast growth, 40.5% from 1980 to 2016 (OPEC, 2017). This growth is due to the globalization of the oil industry (Sahebi, Nickel, & Ashayeri, 2014) that has generated millions of jobs, developed infrastructure, and enhanced economies through a global supply chain. Hence, the study of oil supply chain and its derivatives is of the great importance for the development of the economy of any country in the world, and its study is a main interest for oil companies that must develop strategies to achieve advantages against their competitors (Sahebi, Nickel, & Ashayeri, 2014) mainly by developing supply chain strategies to maximize efficiencies (Chima, 2007) and minimize the costs of production and supply of finished products to consumers (Lisita, Levina, & Lepekhin, 2019). Knowing the

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[1] Professor and Researcher at Universidad Anáhuac México, Facultad de Economía y Negocios. PhD in Transport Engineering and Logistics at Delft University of Technology. Address: Av. Universidad Anáhuac 46, Huixquilucan, Estado de México, 52786, México. Email: rafael.carmona@anahuac.mx ; https://orcid.org/0000-0002-8369-2748

[2] PhD in "Gestión Estratégica y Políticas de Desarrollo" at Universidad Anáhuac México, Facultad de Economía y Negocios. Address: Av. Universidad Anáhuac 46, Huixquilucan, Estado de México, 52786, México.

importance of the energy sector to the economy, in 2013, Mexico enacted an energy constitutional reform that changes, between other things, the supply chain of gasoline obligating Pemex (Mexican state-owned company) to share its pipelines and storage terminals (located at ports, refineries and/or distribution centers) with other oil companies. The main goal of the supply chain of gasoline proposed in the reform is to lower gasoline prices to consumers by enhancing competition and finishing Pemex monopoly. However, in this paper, we analyze the viability of the supply chain of gasoline proposed in this reform, and we find that a supply chain problem is created when multiple oil companies share pipelines and storage terminals to simultaneously distribute different types of gasoline as the reform dictates, because costs increase due to the production of interfaces created each time two different types of gasoline are sequentially shipped through the same pipeline (Fig 1) (an interface is a blend of gasoline called “transmix gasoline” or “mid-grade gasoline" produced and distributed, at the end of each batch, through the same pipeline because of the consecutive distribution of gasoline in a process called batching (Wang et al., 2008)). Therefore, the aim and main contribution of this paper is to design and optimize a supply chain of gasoline that allows multiple oil companies share pipelines and storage terminals to simultaneously distribute different types of gasoline at minimum cost.

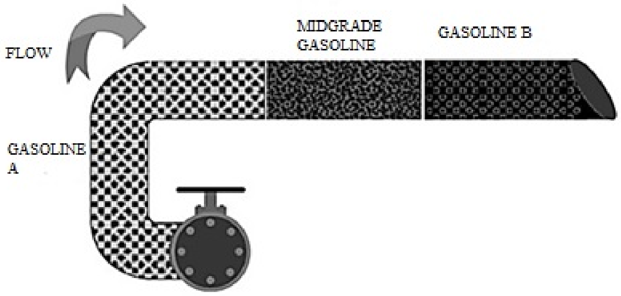

Fig. 1. Gasoline transmix or interface inside a pipeline (Cruz, 2019)

In this paper, the proposed supply chain of gasoline is based in the supply chain strategy of product standardization for distribution, the supply chain management principle of collaboration, and in the supply chain strategy of postponement. Under this principle, companies can gain supply chain advantages when they show willingness-to-cooperate in highly competed supply chain environments, because collaboration with competitors can help companies to achieve huge savings, profit advantages, and opportunities (Zheng et al., 2021; Hussain, Assavapakee & Khumawala, 2006). In the proposed supply chain of gasoline, collaboration is achieved by sharing pipelines and storage terminals, distributing, and storing only one type of gasoline (standard gasoline) through pipelines and common storage terminals (CSTs) and performing the additivation process of gasoline at oil companies’ private storage terminals (PSTs) near customers, rather than at their blending terminals (located inside and/or most commonly outside their refineries’) (U.S. Energy Information Administration [eia], 2021). To achieve this, the proposed supply chain of gasoline applies a supply chain strategy of postponement that consist in the distribution and storage of only one type of gasoline (standard gasoline) through pipelines and CSTs and perform the additivation process of gasoline at oil companies PSTs near customers, rather than at their refineries. Moreover, the proposed supply chain of gasoline allows oil companies to apply a systematic cooperative reciprocal barter, also known as swap collaboration (Hussain, Assavapakee & Khumawala, 2006) by allowing oil companies to swap their stockpiles of standard gasoline between themselves, to minimize costs, lower inventory levels, and reduce the risk of shortages.

A multi-product pipeline inventory-transport problem with stochastic demand and variable lead time is designed to evaluate the viability of the supply chain of gasoline proposed in the reform and the supply chain of gasoline proposed in this paper. This model is a Mixed-Integer Nonlinear Programming Problem (MINLP) that optimizes pipelines and storage terminals (located at ports, refineries and/or distribution centers) used by one or more oil companies to distribute different type of gasoline. The proposed MINLP model minimizes transportation costs, inventory costs, and transmix refining process costs of the supply chain of gasoline of one or more one oil company from CSTs located at the beginning of pipelines to CSTs located at the end of pipelines.

The case study is a small network of Mexico’s gasoline supply chain through pipeline. This network is optimized under three different supply chains: first, the state-owned company distributes different types of gasoline through pipeline (gasoline supply chain before the reform); second, multiple oil companies distribute different types of gasoline through pipelines (gasoline supply chain proposed in the reform); and third, multiple oil companies distribute standard gasoline through pipelines, performing the additivation process of gasoline at oil companies PSTs near customers, rather than at their refineries (gasoline supply chain proposed in this paper). On one hand, the results indicate that oil companies should not share pipelines and storage terminals to distribute and store more than one type of gasoline because supply chain costs increase for all of them (gasoline supply chain proposed in the reform). On the other hand, the results prove that the proposed supply chain of gasoline in this paper allows oil companies to share pipelines and storage terminals to simultaneously distribute different types of gasoline at minimum cost.

The paper is organized as follows. In Section 2, a literature review about supply chain management and optimization in the oil industry is presented. In Section 3, the proposed supply chain based on gasoline standardization with postponement strategy is designed. In Section 4, the mathematical formulation for developing a multi-product pipeline inventory-transport problem with stochastic demand and variable lead time is presented as a MINLP, and an optimal solution methodology is developed to solve this optimization problem. In Section 5, the Mexican gasoline supply chain before the 2013 Mexican energy reform, the gasoline supply chain proposed in the 2013 Mexican energy reform, and the gasoline supply chain proposed in this paper are applied to optimize a small pipeline network of Mexico's gasoline supply chain as study case. Finally, conclusions are included in Section 6.

2. Literature review

Supply chain management involves the design, coordination, and constant improvement of a consecutively organized set of operations to maximize customer services at the lowest cost. The main problems facing oil companies are to minimize the cost of production and distribution of gasoline to customers (Lisitsa, Levina, & Lepekhin, 2019), minimize in-transit inventory and safety stocks at customer facilities, reduce long transportation lead times, maximize production capabilities, and overcome the limitations of modes of transportations (Hussain, Assavapokee & Khumawala, 2006) such as pipelines, vessels or tankers, and railroads. Efficient and cost-effective supply chain management strategies are crucial to solve these problems, the main goal is to establish a supply chain strategy that guarantees constant flow, as much as possible, at a minimum cost. However, the complexity of both products and processes does not make it so obvious (Christopher, Peck, & Towill, 2006; Chopra & Meindl, 2016). Other factors to consider when designing an efficient and cost-effective supply chain are the integration of information technology, information sharing, and collaboration. Information technology is crucial to smooth communication flow along the supply chain network. Information sharing and collaboration increase supply chain efficiency even when it is advantageous to work with competitors (Hussain, Assavapakee & Khumawala, 2006). Oil companies have understood that one way to efficient their supply chains and minimize costs is by collaborating with competitors in a form called systematic cooperative reciprocal barter also known as swaps or exchanges of supplies and assets among competitors (Alperowicz, 2001; Sim, 2002). This technique is classified in three forms of swapping: asset swapping, business swapping, and shipping swapping. An asset swap refers to the exchange of fixed and floating assets between companies. A business swapping refers to the exchange of businesses between companies. A shipping swapping refers to product swapping and sharing arrangement, this form of collaboration minimizes transportation costs, minimizes inventory costs, and maximizes customer services among the participating oil companies (Hussain, Assavapakee & Khumawala, 2006). Knowing the advantage of collaboration, in this paper, a gasoline supply chain strategy based on collaboration in the form of sharing infrastructure and shipping swapping of standard gasoline between competitors is proposed to solve the gasoline supply chain problem presented in Section 1 and explained in Section 3.

Optimization models have been developed to optimize supply chains by maximizing efficiency and minimizing costs. The supply chain of oil can be divided in three segments: upstream, midstream, and downstream (Attia, Ghaithan & Duffuaa, 2019). Different functions are performed for each segment and oil companies can perform the functions of all three segments. The upstream functions are performed by companies that explore, extract, transport, and store crude oil. Aronofsky & Williams (1962) design a mix integer linear problem (MILP) model to decide oil well production rates. Iyer et al. (1998) design a MILP to plan and schedule offshore oil fields' facilities. Nygreen et al. (1998) design a MILP model to determine production and transportation planning. Ierapetritou et al. (1999) design a large-scale MILP model for oil well allocation. Van den Heever et al. (2000; 2001) design a multi period nonlinear model for offshore oil fields' facilities planning to maximize the net present value (NPV) and other economic rules. Kosmidis et al. (2002) design a MILP model for allocation and operation of oil and gas production systems. Mas and Pinto (2003) design a MILP model to optimize the distribution of crude oil through marine terminals, storage tanks, and pipelines. Chryssolouris, Papakostas, Mourtzis (2005) optimize the flow of crude oil from port to refinery tanks and distillation facilities. Carvalho and Pinto (2006a; 2006b) design a MILP model for the assignment of offshore oil fields' facilities. Ulstein et al. (2007) design a MILP model to optimize the production planning of offshore oil fields' facilities. Rocha, Grossmann & Poggi de Aragão (2009) design a model to distribute crude oil from the production site to the refineries. Aizemberg et al. (2014) design a MILP model to transport crude oil from offshore facilities to refineries or petrochemical plants. (Attia, Ghaithan & Duffuaa, 2015) design a multi-objective model to optimize the trade-offs of crude oil and gas. Moradi Nasab & Amin-Naseri (2016) design a MILP model to design pipeline routes and install facilities for crude oil production. Rocha, Grossmann & Poggi de Aragão (2017) design large scale models to optimize the petroleum supply chain.

The midstream functions are performed by companies that refine crude oil at refineries and/or petrochemical plants. Many models have been designed to optimize refineries production, planning, and scheduling (Kazemi & Szmerekovsky, 2015). However, it is important to mention that midstream functions are rarely studied separately from upstream or downstream functions (Attia, Ghaithan & Duffuaa, 2015). Lee et al. (1996) design a model to schedule the supply of crude oil to a refinery. Pinto et al. (2000) design a model to schedule the production of fuel oil, crude oil, liquid petroleum gas, and asphalt in a refinery. Ponnambalam, Vannelli & Woo (1992) and Pinto and Moro (2000) design a model to optimize and plan the production in a refinery. Jia and Ierapetritou (2003) design a multi-period planning model to optimize a refinery. Pitty et al. (2008) design an integrated refinery supply chain dynamic simulator called Integrated Refinery In-Silico (IRIS). Their model optimizes different supply chain operations such as crude oil supply and transportation, and refinery operations. Koo et al. (2008) use Pitty et al. (2008) model to determine the optimal supply chain strategies and optimize capacity investments and policy parameters. Robertson, Palazoglu & Romagnoli (2011) design a nonlinear problem (NLP) for refinery production scheduling and a MILP model unit to optimize refinery operations.

The downstream functions are performed by companies that engage in the distribution of products, storage, blending, additivation, and commercialization of fuel products (Fiorencio et al., 2014). The optimization of the downstream functions mainly addresses the problem of the supply chain of oil network design to assure constant flows (An, Wilhelm & Searcy, 2011). Fernandes, Relvas & Barbosa-Póvoa (2013) design a MILP for strategic planning considering facility locations, transportation modes, and capacities. Fernandes, Relvas & Barbosa-Póvoa (2014) design a MILP for strategic planning considering locations, transportation modes, capacities, and inventory management. Kazemi & Szmerekovsky (2015) design a MILP to determine the optimal location of distribution center, capacities, transportation modes, and transfer volumes. Ghaithan, Ahmed & Duffuaa (2017) design an integrated multi-objective oil and gas supply chain model for tactical decision making for downstream segment. Lima, Relvas & Barbosa-Povoa (2018) designs a multistage stochastic programming model for the optimal distribution of refined products. Attia, Ghaithan & Duffuaa (2019) design a multi-objective optimization model for intermediate-term planning of the supply chain of oil and gas.

3. Gasoline supply chain based on product standardization with postponement strategy

We start this section by explaining a very general view of how gasoline is made to understand the supply chain of gasoline. Refineries make unfinished gasolines also known as gasoline blend stocks. This gasoline is blended with other liquids to make "finished motor gasoline" at blending terminals located inside or most commonly outside refineries (eia, 2021). In fact, there are more blending terminals than refineries around the world (eia, 2021). Finished motor gasolines are basic gasoline that only meets the requirements for fuel to spark ignition engines (eia.gov). These gasolines are blended with other components such as fuel ethanol and detergents to produce base gasolines for customer use (eia, 2021). Finally, gasolines with better qualities are produced during the additivation process, which is the process of adding chemicals known as fuel additives to a base gasoline (fuel without additives) to enhance and/or to provide specific properties to produce gasolines with high octane grades (Sundaram, Venkatasubramanianan, & Caruthers, 2003). These processes are performed in the midstream sector of the supply chain of oil where the refining processes, blending process, storage, and transportation of gasoline take places (Attia, Ghaithan & Duffuaa, 2019). The storage of gasoline at distribution terminals located near the markets, and the distribution of gasoline from distribution terminals to petrol stations take place in the downstream segment (Attia, Ghaithan & Duffuaa, 2019).

As explained in the introduction, the gasoline supply chain strategy proposed in this paper has been designed to show and solve a supply chain problem that arises because of the 2013 Mexican Constitutional Reform. Therefore, for a better understanding, Section 3.1 explains how the state-owned company supplies gasolines in

Mexico before the 2013 Mexican Constitutional Reform was enacted (one company distributes multiple types of gasoline); Section 3.2 explains how the 2013 Mexican Constitutional Reform proposes to share the state-owned company pipelines and CSTs to supply different types of gasoline from different oil companies simultaneously (multiple companies distribute multiple types of gasoline); and Section 3.3 explains the supply chain of gasoline designed in this paper to solve the supply chain problem under study (multiple companies distribute multiple types of gasolines under the proposed strategy).

3.1. Gasoline supply chain before the 2013 Mexican Constitutional Reform

Before the 2013 Mexican Constitutional Reform, the state-owned company was the unique oil company allowed to produce, import, and supply gasoline in Mexico (Cruz, 2019). To satisfy Mexico's gasoline total demand, oil companies supply base gasoline from blending terminals located outside Mexico to the state-owned company CSTs located inside Mexico. These CSTs are located at the ports of entry for import and the state-owned company performs the additivation process using additivation machines, that are located here, to make gasoline with 87 octanes (gasoline A) and 92 octanes (gasoline B). The state-owned company also makes both gasolines at its refineries where other additivation machines are located. Therefore, both gasolines are storage in the state-owned company storage terminals located either at the ports of entry or at its refineries. From there, the state-owned company ships gasoline directly to its storage terminals located near the markets using a fleet of vehicles or train (option 1) or its pipeline network (option 2). Finally, in the last mile, the state-owned company distributes both type of gasoline to petrol stations using fleets of vehicles. In this supply chain, both gasolines mix when they are distributed through the pipeline, producing midgrade gasoline. The state-owned company sells midgrade gasoline as gasoline A. Fig 2 shows how the supply chain of gasoline operates before the 2013 Mexican Constitutional Reform through pipeline (option 2). In this gasoline supply chain, one company distributes multiple types of gasoline.

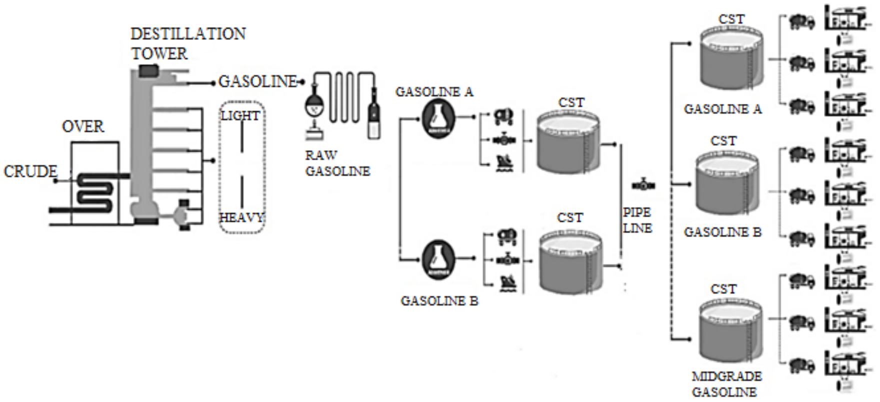

Fig. 2. Gasoline supply chain through pipeline before the reform

3.2. Gasoline supply chain proposed in the 2013 Mexican Constitutional Reform

According with the 2013 Mexican Constitutional Reform, Mexico's gasoline supply chain is redesigned as follows (Cruz, 2019). Private oil companies are allowed to import and supply gasoline to satisfy Mexico's total gasoline demand. The non-imported gasolines are distributed from the state-owned company refineries', where the state-owned company has blending terminals and additive machines, to the state-owned company CSTs located near the markets using fleets of vehicles or train (option 1) or using its pipeline network (option 2). The imported gasolines are distributed from the oil companies' blending terminals outside Mexico, where they perform the additivation process, and ship them to the state-owned company CSTs located at ports of entry for import. From there, oil companies must distribute their gasoline directly to their PSTs located downstream using fleets of vehicles or train (option 1) or by using the state-owned company pipeline network (option 2). However, it is important to mention that currently not all of them have PSTs, so they need to build or rent PSTs located near the markets. In option 2, The state-owned company oversees the distribution of all gasoline through its pipeline. It means, the state-owned company is the distributor of gasoline. Hence, the state-owned company pipelines and CSTs (located at the beginning and end of pipelines) must be shared because gasolines are introduced to pipelines through these terminals. Oil companies therefore rent the distributor pipelines and CSTs to distribute their gasoline through the distributor's pipeline network. Finally, in the last mile, oil companies transport their gasolines to petrol stations using fleets of vehicles. In this supply chain, gasolines are mixed when they are distributed through the pipeline, producing midgrade gasoline. This gasoline cannot be sold as another type of gasoline because midgrade gasoline is produced as a mix of different types of gasoline owned by different oil companies. Fig 3 shows a scheme of Mexico's gasoline supply chain through pipeline according with the 2013 Mexican Constitutional Reform when two oil companies share the state-owned company pipelines and CSTs. In this case, gasoline A and gasoline B are two different types of gasoline sold by oil company 1, whilst gasoline C and gasoline D are two different types of gasoline sold by oil company 2, and midgrade gasoline are different mixes of gasoline produced by the combination of these four types of gasolines when they are distributed simultaneously through the same pipeline network and CSTs. In this gasoline supply chain, multiple oil companies distribute multiple types of gasoline through the same pipeline network and storage terminals.

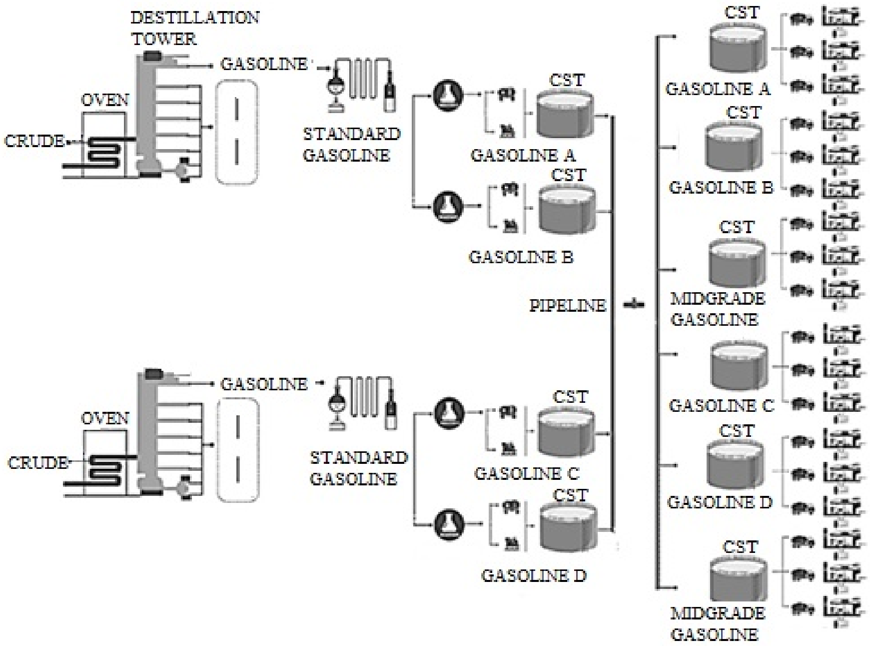

Fig. 3. Gasoline supply chain through pipeline proposed in the reform

3.3. Gasoline supply chain based on product standardization with postponement strategy

In this section, a supply chain is designed to maximize infrastructure capacities and minimize costs of the distribution of gasoline of one or multiple oil companies that distribute multiple types of gasoline through the same pipeline network and storage terminals. This gasoline supply chain is based on a strategy of gasoline standardization, the supply chain strategy of postponement, and in the supply chain principle of collaboration with the aim of allowing multiple oil companies to use the same pipelines and storage terminals at lower costs than the 2013 Mexican Constitutional Reform strategy for the distribution of gasoline explained in Section 3.2. The proposed gasoline supply chain is as follows (Fig 4):

1) Oil companies can only distribute base gasolines through the distributor's pipelines (supply chain management principle of collaboration) that fall within the predefined parameters of the standard gasoline to ensure the same quality and market value because these gasolines are going to mix in inside pipelines.

2) Oil companies can only store standard gasoline at the distributor's CSTs (supply chain management principle of collaboration).

3) Oil companies must have or rent PSTs located downstream the gasoline supply chain near markets.

4) Oil companies must transport standard gasoline from CSTs located at the end of pipelines to their PSTs.

5) In parallel, oil companies must transport fuel additives to their PSTs.

6) Oil companies must move the additivation process from their blending terminals to their PSTs (downstream) where this process must take place (postponement strategy). Therefore, oil companies produce and store different types of gasoline at their PSTs.

7) In the last mile, oil companies transport their gasolines to petrol stations by road.

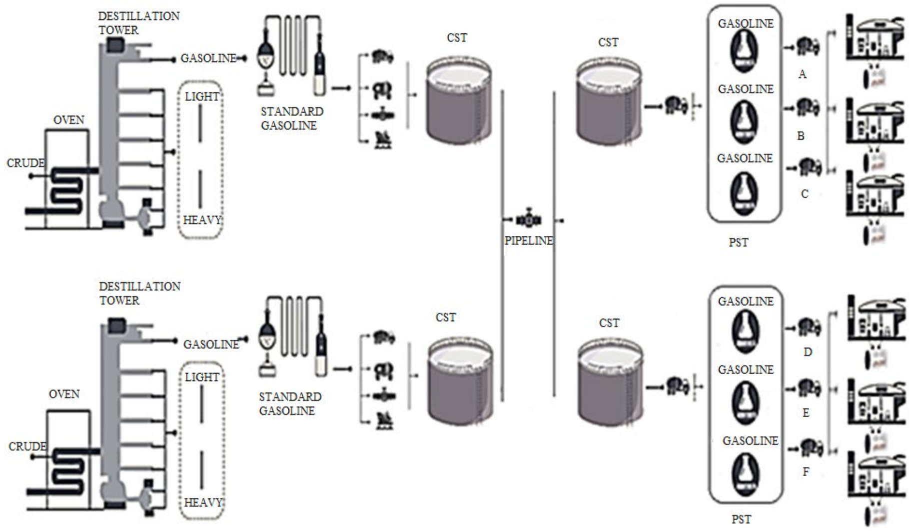

Fig. 4. Gasoline supply chain based on product standardization with postponement strategy

The proposed gasoline supply chain is designed based on: product standardization, the supply chain management principle of collaboration, a supply chain management strategy of postponement, and the 7 factors involved in the sustainability of a supply chain (Hines, 2014) (Table 1). The aim is to minimize costs through proper management and maximize the variety of products that coexist in a multiproduct inventory distribution network. This gasoline supply chain allows demand to be met for different types of gasoline without incurring high operating costs that impact on gasoline prices.

In a supply chain, collaboration between companies helps them to achieve savings, profits, and opportunities (Zheng et al., 2021; Hussain, Assavapakee & Khumawala, 2006). In this gasoline supply chain, collaboration between oil companies is achieved by distributing and storing only one type of gasoline (standard gasoline) through shared pipelines and CSTs, and performing the additivation process of gasoline at oil companies' private storage terminals (PSTs) (downstream) near customers, rather than at their blending terminals (midstream) in a postponement strategy. This type of collaboration presents huge logistics advantages because allows oil companies to apply a systematic cooperative reciprocal barter collaboration also known as swap collaboration (Hussain, Assavapakee & Khumawala, 2006). This type of collaboration allows oil companies to swap their stockpiles of standard gasoline between them, to lower inventory levels and reduce the risk of shortages.

Table 1 explains the proposed gasoline supply chain by assessing the concepts of value, volume, speed, visibility, volatility, variety, and variability.

Table 1. Key characteristics for the proposed gasoline supply chain

Key factors	Description
Value	Oil companies add value downstream the gasoline supply chain by moving the additivation process to their PSTs near markets achieving competitive and logistics advantages as leaders in services and costs (Cristopher, 2016). As service leaders, oil companies can expand product offerings, meaning they can sell different types of gasoline without limitations because they distribute standard gasoline and then differentiate their gasolines at their PSTs. As cost leaders, distributing only one type of gasoline allows a continuous flow of gasoline what reduces the number of interfaces and inventory levels by reducing lead times to the minimum (Um, Lyons, Lam, Cheng, & Dominguez-Pery, 2017) by achieving economies of scale through product standardization (Cheng et al., 2010).
Volume	Moving the additivation process to the oil companies PSTs near markets (downstream) allows the distribution of a standard gasoline, which increases the volume of gasoline that can be distributed through the pipeline network and stored at CSTs. Essentially, volume grows because oil companies can get standard gasoline from CSTs any time because standard gasoline continuously flows through the pipeline without interruption and the inventory cycle of a

	standard gasoline is faster than that of many gasolines separately. Increasing volume allows to achieve economies of scale and reduce costs.
Velocity/speed/ flexibility	A supply chain based on a postponement strategy improves speed, agility, and flexibility (Li et al., 2016; Jabbarzadeh, Haughton, & Pourmehdi, 2019). Speed is improved because delivery times for distributing a standard gasoline through a pipeline network are reduced to the minimum. Flexibility is improved because oil companies can make different types of gasoline near customers, production operations can shift quickly among different types of gasolines, which allows for a quicker response to customer demand (Jin-Hai, Anderson, & Harrison 2003; Dubey and Gunasekaran, 2015). Increasing velocity/speed/flexibility allows to achieve economies of scale and reduce costs.
Visibility	Visibility is defined as “the extent to which actors within the supply chain have access to or share information for a mutual benefit" (Ahimbisibwe, Ssebulime, Tumuhairwe, & Tusiine, 2016). In the proposed supply chain of gasoline, the required level of visibility is high to allow oil companies to pick up standard gasoline from a batch that does not belong to them, so standard gasoline flows continuously through the pipelines, and lead times can be reduced to the minimum. Hence, oil companies must report to the distributor, who controls, the amount of standard gasoline they push and pull from the pipeline at any time.
Volatility	Volatility, uncertainty, the risk of having stock outs, and the inability to meet customers demand are mitigated because lead times are minimized (Zsidisin, 2003) due to the continuous flow of standard gasoline through pipelines, and oil companies can pick up standard gasoline from CSTs (downstream) any time.
Variety	Variety is high since many types of gasoline can be produced, distributed, and sold when distributing standard gasoline and then differentiate their gasolines at their PSTs. Randall & Ulrich (2001) report that variety increases production costs and market mediation costs. In the proposed gasoline supply chain, production costs increase because oil companies must invest, locate fuel-additive machines at their PSTs (downstream) and distribute additives to their PSTs. However, market mediation costs decrease because most of the cyclical and safety inventories are stored as standard gasoline, lead times are reduced to the minimum reducing the risk of having a stockout or excess inventory, and levels of inventory are minimized for each type of gasoline by storing standard gasoline.
Variability	The distribution of a single type of gasoline reduces the variability of demand by aggregating it, making it more predictable and easier to forecast (Germain, Claycomb & Droge, 2008).

4. Problem description and formulation

A multi-product pipeline supply chain inventory-transport problem with stochastic demand and variable lead time, which is a Mixed-Integer Nonlinear Programming Problem (MINLP), is developed in this section. This model minimizes the operations costs of the gasoline supply chain through pipeline by the optimal management of the pipelines and the storage terminals connected to pipelines. The model determines optimal batch sizes, inventory levels (under a continuous inventory policy), number of shipments, and the amount of product to be delivered such that the total costs, for all companies using the same infrastructure (pipeline network and common storage terminals) are minimized.

4.1 Problem description

1) Multiple oil companies, multiple types of gasoline, one distributor.
2) The distributor owns the supply facilities, transshipment facilities, demand facilities, and pipelines that are used to distribute multiple types of gasoline by multiple oil companies.
3) The pipeline network can be described as a graph where the vertices are the supply facilities and the demand facilities, and the arcs are connections of pipelines that links a supply facility with a demand facility. Each pair of vertices can be linked by more than one arc where different pipelines are connected by transshipment facilities, creating all the possible routes between them.
4) In the supply facilities, the distributor owns a certain number of CSTs with limited storage capacity.
5) Transshipment facilities are valves that change the course of gasoline flow through the pipeline network, no charge or discharge of gasoline happens at these facilities. Hence, the problem presented in this paper is not a transshipment problem but a transportation problem.
6) A batch is the quantity of gasoline demanded at a demand facility, that is shipped through an arc from a supplier facility per shipment. Therefore, batches are not divisible to prevent loss of gasoline and to maintain the quality of the batch.
7) In the demand facilities, the distributor owns a certain number of CSTs with limited storage capacity.
8) One or more than one oil company can simultaneously use the distributor pipelines and CSTs to supply gasoline to demand facilities located downstream the gasoline supply chain.
9) For the different types of gasoline, the demand is stochastic, daily average demands, and daily average standard deviations are known over a planning time horizon.

10) Gasoline demands must be fulfilled with a cycle service level inventory policy of ($1-\alpha_{jp}$) in the planning time horizon or time in which they occur.
11) Shortage is allowed but backordering is not allowed.
12) Lead times at demand facilities are stochastic. Average lead times and average lead times standard deviations are known for all arcs.
13) Transportation costs are known per cubic meter for the different types of gasoline and for all arcs.
14) Ordering costs are known per order and gasoline type.
15) The storage costs or holding costs are known per gasoline type for all demand facilities per cubic meter.
16) Transmix refining process costs per cubic meter are known per gasoline type
17) Average midgrade gasoline volumes per cubic meter per gasoline type created for all arcs
18) Gasoline flows through the arcs of the pipeline network are limited to the maximum capacity that can be reached by the pipeline pumps per day, and it can be zero when product is not being pumped.
19) All pipelines in the network are always full of gasoline.
20) Storage tanks cannot receive and deliver gasoline at the same time (Joly, Moro, & Pinto, 2002) (Kemp, 2015). Hence, the size of the batch shipped to a CST must be smaller than or equal to the storage capacity of the tank assigned to store the batch, otherwise, the pipeline would be stopped until the tank has storage capacity once again.

4.2 Decisions

Transportation decisions: How much gasoline and how many shipments must be sent through the arcs of the pipeline network (from supply facilities to demand facilities) during the planning time horizon? What is the optimal amount of gasoline to supply at supplier facilities during the planning time horizon?

Inventory decisions: What is the average charge flow to upload each different type of gasoline at each demand facility? What is the average discharge flow to download each different type of gasoline at each demand facility? What is the optimum batch size or optimal order quantity that minimizes total cost (inventory costs, ordering costs, transportation costs, and refining mid-grade gasoline costs) of each demand facility per gasoline type? What is the final inventory at each supplier facility and at each demand facility per gasoline type?

Before presenting the mathematical model, the notation used throughout the paper is as follows:

4.3 Index sets

I	set of supplier facilities ($i \in I$)
J	set of demand facilities ($j \in J$)
P	set of gasoline products ($p \in P$)
R	set of arcs ($r \in R$)
L	set of pipelines ($l \in L$)

4.4 Parameters and notations

TH	Planning Time Horizon or Number of Time Periods per time (e.g., if One Time Period = 1 day and 1 time = 1 year, then $TH = 365$)	[-]
K_i	Supply capacity at facility i during TH	[m^3]
D_{jp}	Average demand of gasoline p at facility j during TH	[m^3]
c_p	Purchase cost per m^3 of gasoline p	[\$/m^3]
β_p	Price per m^3 of gasoline p	[\$/m^3]
β_{mdg}	Price per m^3 of midgrade gasoline	[\$/m^3]
$CTRA_{ijpr}$	Transport cost per m^3 of gasoline p shipped through arc r from facility i to facility j	[\$/m^3]
S_p	Ordering cost of gasoline p per order	[\$]
H_{jp}	Excess holding Cost of gasoline p at demand facility j per order	[\$ /m^3]
Cm_{ijpr}	Cost paid for transporting to a refinery and for refining mid-grade gasoline produced when gasoline p is shipped through arc r from facility i to facility j	[\$/m^3]
Vm_{ijpr}	Average amount of mid-grade gasoline produced when one order or one batch of gasoline p is shipped through arc r from facility i to facility j per order	[m^3]

μ_{Lijpr}	Expected number of Time Periods for Lead Time of gasoline *p* shipped through arc *r* from facility *i* at demand facility *j*	[-]
σ_{Lijpr}	Standard Deviation of Time Periods for Lead Time of gasoline *p* shipped through arc *r* from facility *i* at demand facility *j*	[-]
μ_{djp}	expected demand of gasoline *p* at demand facility *j* during One Time Period	[m^3]
σ_{djp}	Standard Deviation of Demand of gasoline *p* at demand facility *j* during One Time Period	[m^3]
μ_{DLijpr}	Expected Demand of gasoline *p* at demand facility *j* over Lead Time per order	[m^3]
σ_{DLijpr}	Standard Deviation of Demand of gasoline *p* at demand facility *j* over Lead Time per order	[m^3]
α_{jp}	Probability of a stock out of gasoline *p* at demand facility *j*	
$1\text{-}\alpha_{jp}$	Cycle service level inventory policy of gasoline *p* at demand facility *j*	[-]
SS_{ijpr}	Safety Stock of gasoline *p* at demand facility *j* over Lead Time per order	[m^3]
$CAPW_{jp}$	Total storage capacity of gasoline *p* at demand facility *j* per order	[m^3]
Io_{ip}	gasoline *p* initial inventory at supplier facility *i* during *TH*	[m^3]
Io_{jp}	gasoline *p* initial inventory at demand facility *j* during *TH*	[m^3]
$Fdmax_{jp}$	customer *j* maximum discharge flow capacity during One Time Period	[m^3]
$Fpmaxl_l$	pipeline *l* maximum flow capacity during One Time Period	[m^3]
Y_{rl}	1 if pipeline *l* is part of arc *r*, 0 otherwise	[-]
td_{jp}	Expected number of Time Periods for discharge flow of gasoline *p* at demand facility *j*	[-]
tc_{ijpr}	Expected number of Time Periods for charge flow of gasoline *p* into demand facility *j* shipped through arc *r* from supplier facility *i*	[-]
n_i	Number of storage tanks available at demand facility *i*	[-]
n_j	Number of storage tanks available at demand facility *j*	[-]

4.5 Decision variables

O_{ip}	Supply of gasoline *p* at facility *i* during *TH*	[m^3]
Q_{ijpr}	Batch size gasoline *p* shipped through arc *r* from supplier facility *i* to demand facility *j* in one order (shipment)	[m^3]
d_{ijpr}	Amount of gasoline *p* shipped through arc *r* from supplier facility *i* to demand facility *j* during *TH*	[m^3]
X_{ijpr}	Number of orders or batches of gasoline *p* shipped through arc *r* from supplier facility *i* to demand facility *j* during *TH*	[-]
Fc_{ijpr}	Average charge flow of gasoline *p* into demand facility *j* shipped through arc *r* from supplier facility *i* during One Time Period	[m^3]
Fd_{jijpr}	Average discharge flow of gasoline *p* at demand facility *j* during One Time Period	[m^3]
If_{ip}	Gasoline *p* final inventory at supplier facility *i* during *TH*	[m^3]
If_{jp}	Gasoline *p* final inventory at demand facility *j* during *TH*	[m^3]

4.6 Objective function

The objective function includes the following costs:

The total amount of gasoline *p* to buy (Eq. 1) and transport (Eq. 2) is equal to the total amount of gasoline *p* demanded by demand facilities plus the total average amount of mid-grade gasoline produced when batches of gasoline *p* are shipped through arcs of the pipeline system.

(Eq. 1) calculates the total purchase cost (*PC*) and opportunity cost (*OPOC*) for the *TH*:

$$PC + OPOC = \sum_{j=1}^{J}\sum_{p=1}^{P} c_p\left(D_{jp} - Io_{jp}\right) + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R}\left(c_p + \left(\beta_p - \beta_{mdg}\right)\right)X_{ijpr}Vm_{ijpr} \tag{1}$$

(Eq. 2) calculates the total cost of transportation (*TRAC*) for the *TH*:

$$TRAC = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R}\left[CTRA_{ijpr}X_{ijpr}\left(Q_{ijpr} + Vm_{ijpr}\right)\right] \tag{2}$$

(Eq. 3) calculates the total cost of ordering (*OC*) for the *TH*:

$$OC = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} S_{jp} X_{ijpr} \tag{3}$$

(Eq. 4) calculates the total cost of interfaces (*MGC*) for the *TH*. The cost considers transporting mid-grade gasoline from demand facility *j* to a refinery, and the cost of refining the mid-grade gasoline (transmix refining process):

$$MGC = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} X_{ijpr} Cm_{ijpr} Vm_{ijpr} \tag{4}$$

Fig 5 shows the inventory level of gasoline through time per order quantity or batch size (Q_{ijpr}). The inventory level includes the cycle inventory and the safety inventory or safety stock (SS_{ijpr}). Fig 5 illustrates the average time (Δt_{ijpr}) it takes for demand facility *j* to consume Q_{ijpr}. In Fig 5, the positive slope of the inventory level line is equal to Fc_{ijpr}. This slope indicates when gasoline *p* is being loaded into demand facility *j* from supplier facility *i* through arc *r* during time tc_{ijpr} with an average charging flow equal to Fc_{ijpr}. The negative slope of the inventory line is equal to Fd_{ijpr}. This slope indicates demand facility *j*'s average discharge flow or consumption rate for gasoline *p* during time td_{ijpr}. Hence, the inventory cost (HC_{ijpr}) for storing Q_{ijpr} is calculated as follows:

$$HC_{ijpr} = H_{jp}\left(X_{ijpr}\int Q_{ijpr}(t)\,dt\right) = H_{jp} X_{ijpr} Q_{ijpr}\left(\frac{1}{Fc_{ijpr}} + \frac{1}{Fd_{ijpr}}\right)\left(SS_{ijpr} + \frac{Q_{ijpr}}{2}\right) \tag{5}$$

Where:

$$SS_{ijpr} = F(\alpha_{jp})^{-1}\sqrt{\mu_{Lijpr}\sigma_{djp}^{2} + \mu_{djp}^{2}\sigma_{Lijpr}^{2}} = F(\alpha_{jp})^{-1}\sqrt{\mu_{Lijpr}\sigma_{djp}^{2} + \left(D_{jp}/TH\right)^{2}\sigma_{Lijpr}^{2}} \tag{6}$$

The total cost of inventory (*HC*) for the *TH* is equal to the sum of all customers HC_{ijpr} plus initial inventory costs minus final inventory costs at all the supply chain facilities (Eq. 7).

$$HC = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} HC_{ijpr} + \sum_{j=1}^{J}\sum_{p=1}^{P} H_{jp}\left(Io_{jp} - If_{jp}\right) + \sum_{i=1}^{I}\sum_{p=1}^{P} H_{ip}\left(Io_{ip} - If_{ip}\right) \tag{7}$$

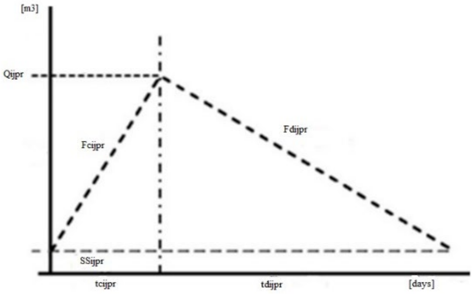

Fig. 5. Inventory level per batch Q_{ijpr}

The sum of (Eq. 1), (Eq. 2), (Eq. 3), (Eq. 4) and (Eq. 7) calculates the total cost (*TC*) of the multi-product pipeline supply chain inventory-transshipment problem with stochastic demand and variable lead time for the *TH*.

The problem formulation is as follows:

$$\begin{aligned}\min TC: &\sum_{j=1}^{J}\sum_{p=1}^{P} c_p\left(D_{jp} - Io_{jp}\right) + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R}\left(c_p + \left(\beta_p - \beta_{mdg}\right)\right) X_{ijpr} Vm_{ijpr} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} CTRA_{ijpr} X_{ijpr}\left(Q_{ijpr} + Vm_{ijpr}\right) + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} S_{jp} X_{ijpr} + \\ &\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} X_{ijpr} Cm_{ijpr} Vm_{ijpr} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} H_{jp} X_{ijpr} Q_{ijpr}\left(\frac{1}{Fc_{ijpr}} + \frac{1}{Fd_{ijpr}}\right)\left(SS_{ijpr} + \frac{Q_{ijpr}}{2}\right) + \sum_{j=1}^{J}\sum_{p=1}^{P} H_{jp}\left(Io_{jp} - If_{jp}\right) + \sum_{i=1}^{I}\sum_{p=1}^{P} H_{ip}\left(Io_{ip} - If_{ip}\right)\end{aligned} \tag{8}$$

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$$\sum_{j=1}^{J}\sum_{r=1}^{R} d_{ijpr} + If_{ip} = O_{ip} + Io_{ip} \quad \forall i \in I; p \in P \tag{9}$$

$$\sum_{i=1}^{I}\sum_{r=1}^{R} d_{ijpr} + Io_{jp} = D_{jp} + If_{jp} \quad \forall j \in J; p \in P \tag{10}$$

$$\sum_{p=1}^{P} O_{ip} \le K_i \quad \forall i \in I \tag{11}$$

$$Q_{ijpr} \le CAPW_{jp} \quad \forall i \in I; j \in J; p \in P; r \in R \tag{12}$$

$$\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} \frac{d_{ijpr}}{Fd_{ijpr}} \le n_i TH \quad \forall i \in I \tag{13}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{r=1}^{R} \frac{d_{ijpr}}{Fd_{ijpr}} \le n_j TH \quad \forall j \in J \tag{14}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} \left(d_{ijpr} + X_{ijpr} Vm_{ijpr} \right) Y_{rl} \le Fpmaxl_l TH \quad \forall l \in L \tag{15}$$

$$Fd_{ijpr} \le Fdmax_{jp} \quad \forall j \in J; p \in P \tag{16}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{r=1}^{R} \frac{d_{ijpr}}{Fc_{ijpr}} \le n_j TH \quad \forall j \in J \tag{17}$$

$$Fc_{ijpr} \le Fpmaxl_l Y_{rl} \quad \forall i \in I; j \in J; p \in P; r \in R; l \in L \tag{18}$$

$$Fd_{ijpr} \le Fc_{ijpr} \quad \forall i \in I; j \in J; p \in P; r \in R \tag{19}$$

$$d_{ijpr} - X_{ijpr} Q_{ijpr} = 0 \quad \forall i \in I; j \in J; p \in P; r \in R \tag{20}$$

$$Fd_{ijpr} \ge \mu_{djp} \quad \forall i \in I; j \in J; p \in P; r \in R \tag{21}$$

$$d_{ijpr} \ge 0 \quad \forall i \in I; j \in J; p \in P; r \in R \tag{22}$$

$$Q_{ijpr} > 0 \quad \forall i \in I; j \in J; p \in P; r \in R \tag{23}$$

$$Fc_{ijpr} > 0 \quad \forall i \in I; j \in J; p \in P; r \in R \tag{24}$$

$$0 \le If_{ip} \ge CAPW_{ip} \quad \forall i \in I; p \in P \tag{25}$$

$$0 \le If_{jp} \le CAPW_{jp} \quad \forall j \in J; p \in P \tag{26}$$

$$X_{ijpr} \in Z^{+} \quad \forall i \in I; j \in J; p \in P; r \in R \tag{27}$$

The model minimizes the total expected cost in the *TH* (Eq. 8) consisting of the cost of gasoline purchase and opportunity (first and second terms), the cost of transportation (third term), the cost of ordering (fourth term), the cost of refining mid-grade gasoline (fifth term), and the expected cost of inventory (sixth, seventh, and eighth terms). The inventory cost adds the cost of initial inventories at supplier and demand facilities that is paid in the *TH* and subtracts the cost of the final inventories at supplier and demand facilities that must be paid in the following *TH*. Constraints (Eq. 9) balance the supply for supplier facilities. Constraints (Eq. 10) balance the demand for customer facilities. Constraints (Eq. 11) make sure that the supply of gasoline from supplier facility i is less than its total supplier capacity. Constraints (Eq. 12) are the storage capacity restrictions associated with the customer facility *j* for gasoline *p*. These constraints make sure that gasoline *p* batch sizes are smaller than or equal to the storage capacity of the tank assigned to store the batch at customer facility *j*. Constraints (Eq. 13) make sure that the total time to discharge gasoline from supply facility *i* must be less than *TH* multiplied by the total number of storage tanks *n* located at supply facility *i*. Constraints (Eq. 14) make sure that the total time to discharge gasoline from demand facility *j* must be less than *TH* multiplied by the total number of storage tanks *n* located at demand facility *j*. Constraints (Eq. 15) indicate that the total amount of gasoline shipped through pipeline *l* must be smaller than or equal to pipeline *l*'s maximum flow capacity. Constraints (Eq. 16) indicate that the average discharge flow to download gasoline *p* from customer facility *j* must be smaller than or equal to its maximum discharge flow capacity. Constraints (Eq. 17) make sure that the total time of charging gasoline at demand facility j must be less than the TH multiplied by the total number of storage tanks n located at demand facility j. Constraints (Eq. 18) indicate that the average charge flow needed to upload gasoline p to customer facility j from supplier facility i through arc r must be smaller than or equal to pipeline l's maximum flow capacity. Constraints (Eq. 19) indicate that the average discharge flow to download gasoline p from customer facility j must be smaller than or equal to the average charge flow needed to upload gasoline p to customer facility j from supplier facility i through arc r. This is because gasoline storage tanks take longer to upload than to download when they receive gasoline through the pipeline. Constraints (Eq. 20) make sure that the amounts of gasoline shipped from supplier facility i to customer facility j through arc r is equal to the number of shipments send from supplier facility i to customer facility j through arc r multiplied by the optimal batch size. Constraints (Eq. 21) enforce the average discharge flow to be higher than the expected demand of gasoline p at demand facility j over lead time. Otherwise, the demand of facility j cannot be satisfied. Constraints (Eq. 22) enforce the non-negativity restrictions on the total amount of gasoline shipped from supplier facility i to customer facility j through arc r in the TH. Constraints (Eq. 23 and Eq. 24) enforce the non-negative restrictions on the optimal batch sizes, the average charge flows, and the average discharge flow, but they cannot be zero. Constraints (Eq. 25 and Eq. 26) enforce the non-negativity restrictions on the final inventory at supplier facilities and customer facilities respectively. These constraints also make sure that the final inventories of gasoline p at supplier facilities and customer facilities are smaller than or equal to their storage capacities for gasoline p. Finally, constraints (Eq. 27) enforce the integrality restriction on the number of shipments variables.

4.7. Optimal solution methodology

In this section, an optimal solution methodology is proposed for solving the mathematical formulation. The methodology optimizes the proposed MINLP model (Eq. 8 to Eq. 27) variables (O_{ip}, d_{ijpr}, Q_{ijpr}, X_{ijpr}, Fc_{ijpr}, Fd_{ijpr}, If_{ip}, and If_{jp}).

The total number of shipments X_{ijpr} is equal to d_{ijpr}/Q_{ijpr} (Eq.20). By substituting $X_{ijpr}=d_{ijpr}/Q_{ijpr}$ in (Eq. 1), (Eq. 2), (Eq. 3) and (Eq. 7), it is possible to calculate the total cost in terms of d_{ijpr}, Q_{ijpr} and Fc_{ijpr} for the TH (Eq. 8). Hence, (Eq. 8) can be expressed as (Eq. 28). By studying (Eq. 28), the objective function (Eq. 8) is convex in $Q_{ijpr} > 0$, $Fc_{ijpr} > 0$ and $Fd_{ijpr} \geq \mu_{djp}$. Hence, from Eq. 28, it is possible to compute the optimal value of Q^*_{ijpr}, for any value of d_{ijpr} by taking the derivative of the objective function with respect to Q_{ijpr} (Eq. 29).

$$\begin{aligned}\min TC: &\sum_{j=1}^{J}\sum_{p=1}^{P} c_p\left(D_{jp}-Io_{jp}\right)+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R}\left[\frac{d_{ijpr}}{Q_{ijpr}}\left(\left(c_p+\left(\beta_p-\beta_{mdg}\right)\right)Vm_{ijpr}+CTRA_{ijpr}\left(Q_{ijpr}+Vm_{ijpr}\right)+S_{jp}+Cm_{ijpr}Vm_{ijpr}\right)\right] \\ &+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R} H_{jp}\left[d_{ijpr}\left(\frac{1}{Fc_{ijpr}}+\frac{1}{Fd_{ijpr}}\right)\left(SS_{jp}+\frac{Q_{ijpr}}{2}\right)\right]+\sum_{j=1}^{J}\sum_{p=1}^{P} H_{jp}\left(Io_{jp}-If_{jp}\right)+\sum_{I=1}^{I}\sum_{p=1}^{P} H_{ip}\left(Io_{ip}-If_{ip}\right)\end{aligned} \tag{28}$$

$$Q_{ijpr}=\sqrt{\frac{2\left(S_{jp}+\left(c_p+\left(\beta_p-\beta_{mdg}\right)+CTRA_{ijpr}+Cm_{ijpr}\right)Vm_{ijpr}\right)}{H_{jp}\left(\frac{1}{Fc_{ijpr}}+\frac{1}{Fd_{ijpr}}\right)}} \tag{29}$$

In Eq. 29, the optimal value of Q^*_{ijpr} depends on finding the optimal value of Fc^*_{ijpr} and Fd^*_{ijpr}, and it is constrained to the storage capacity of the tank $CAPW_{jp}$ assigned to store the batch at the distributor's CSTs (Eq. 12). Hence, the optimal values of Fc^*_{ijpr} and Fd^*_{ijpr} must be found to solve the optimal value of Q^*_{ijpr}. However, the limit of the model objective function (Eq. 28) as Fc_{ijpr} and Fd_{ijpr} approaches infinity is zero. In other words, as Fc_{ijpr} and Fd_{ijpr} increases, the TC_{ijpr} decreases without limit. The limit of the model objective function (Eq. 28) as Fc_{ijpr} and Fd_{ijpr} increases, proves that the optimal values of Fc^*_{ijpr} and Fd^*_{ijpr} must be upper-bound constrained, otherwise the optimal values of Fc^*_{ijpr}, Fd^*_{ijpr}, and Q^*_{ijpr} cannot be found. Constraints (Eq. 16 and Eq. 19) are upper bound constraints for Fd_{jp}, (Eq. 18) are upper bound constraints for Fc_{ijpr}, and (Eq. 12) are upper bound constraints for Q_{ijpr} and therefore to Fc_{ijpr} and Fd_{jp}. Consequently:

- Case 1: the optimal values of Fc^*_{ijpr} are equal to $Fpmaxl_l$ and the optimal values of Fd^*_{jp} are equal to $Fdmax_{jp}$ only if the calculated values of Q^*_{ijpr} are smaller than or equal to the storage capacity of the tank $CAPW_{jp}$ assigned to store the batch at the distributor's CSTs (Eq. 12) and if $Fdmax_{jp}$ is smaller than or equal to $Fpmaxl_l$ (Eq. 19).

- Case 2: the optimal values of Fc^*_{ijpr} and Fd^*_{ijpr} are equal to $Fpmaxl_l$ when $Fdmax_{jp}$ is greater than $Fpmaxl_l$ and the calculated values of Q^*_{ijpr} are smaller than or equal to the storage capacity of the tank $CAPW_{jp}$ assigned to store the batch at the distributor's CSTs (Eq. 12).

- Case 3: Q^*_{ijpr} must be equal to $CAPW_{jp}$ when the calculated values of Q^*_{ijpr}, in case 1 and in case 2, are greater than the storage capacity of the tank $CAPW_{jp}$ assigned to store the batch at the distributor's CSTs, otherwise they unfulfilled (Eq. 12). In this case, Fc^*_{ijpr} and Fd^*_{ijpr} must be equal to minimize the time that a batch of gasoline p is stored at the distributor's CSTs. Knowing this, if Fc^*_{ijpr} and Fd^*_{ijpr} are equal, (Eq. 30) calculates the optimal values of Fc^*_{ijpr} and consequently Fd^*_{ijpr} for this case.

$$Fc_{ijpr} = \frac{H_{jp} CAPW_{jp}^2}{\left(S_{jp} + \left(c_p + \left(\beta_p - \beta_{mdg}\right) + CTRA_{ijpr} + Cm_{ijpr}\right) Vm_{ijpr}\right)} \qquad (30)$$

The flow diagram shown in Fig 6 demonstrates how to calculate the optimal values of Fc^*_{ijpr}, Fd^*_{ijpr}, and Q^*_{ijpr}.

Finally, the remaining MILP model (Eq. 31 to Eq. 43) is a capacitated transportation problem that can be solved with any standard branch-and-bound method. In this paper, branch-and-cut algorithm is applied to find the optimum values of the continuous and integer variables of this MILP model. Finally, the solution to the MILP model (Eq. 32 to Eq. 41) leads to the solution of the proposed MINLP model (Eq. 8 to Eq. 23). Its solution determines optimal batch sizes, flow charges, inventory levels (under a continuous inventory policy), number of shipments, and the demand for the product to be delivered.

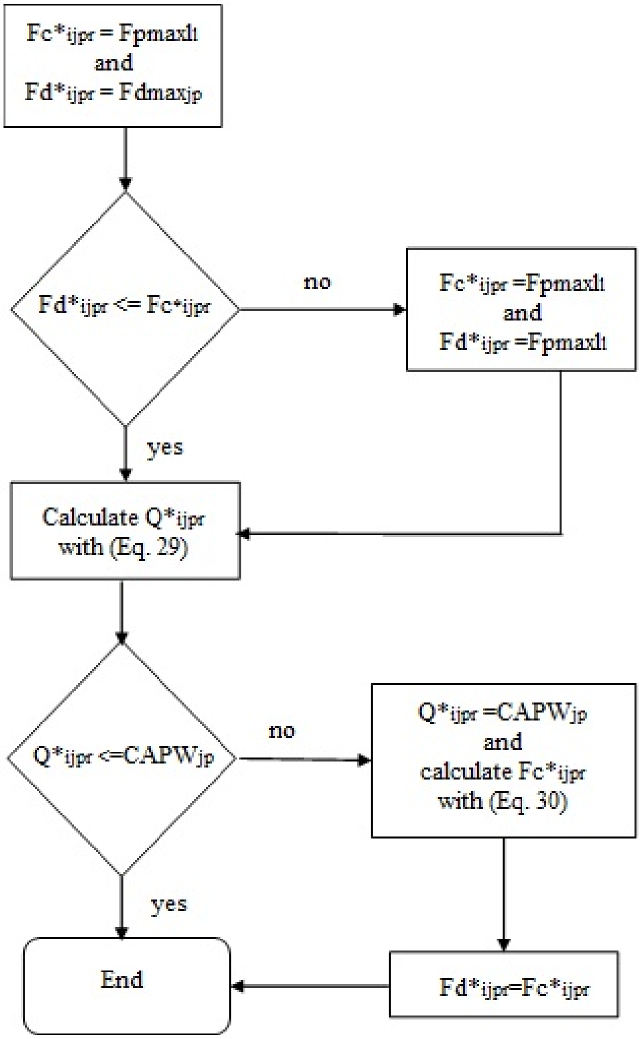

Fig. 6. Optimal values of Fc^{*}_{ijpr}, Fd^{*}_{ijpr}, and Q^{*}_{ijpr}.

$$\begin{aligned}\min TC:&\sum_{j=1}^{J}\sum_{p=1}^{P}c_p\left(D_{jp}-Io_{jp}\right)+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R}\left[\frac{d_{ijpr}}{Q_{ijpr}}\left(\left(c_p+\left(\beta_p-\beta_{mdg}\right)\right)Vm_{ijpr}+CTRA_{ijpr}\left(Q_{ijpr}+Vm_{ijpr}\right)+S_{jp}+Cm_{ijpr}Vm_{ijpr}\right)\right]\\&+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R}H_{jp}\left[d_{ijpr}\left(\frac{1}{Fc_{ijpr}}+\frac{1}{Fd_{ijpr}}\right)\left(SS_{jp}+\frac{Q_{ijpr}}{2}\right)\right]+\sum_{j=1}^{J}\sum_{p=1}^{P}H_{jp}\left(Io_{jp}-If_{jp}\right)+\sum_{I=1}^{I}\sum_{p=1}^{P}H_{ip}\left(Io_{ip}-If_{ip}\right)\end{aligned}\tag{31}$$

ST

$$\sum_{j=1}^{J}\sum_{r=1}^{R}d_{ijpr}+If_{ip}=O_{ip}+Io_{ip}\quad\forall i\in I;p\in P\tag{32}$$

$$\sum_{i=1}^{I}\sum_{r=1}^{R}d_{ijpr}+Io_{jp}=D_{jp}+If_{jp}\quad\forall j\in J;p\in P\tag{33}$$

$$\sum_{p=1}^{P}O_{ip}\le K_i\quad\forall i\in I\tag{34}$$

$$\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R}\frac{d_{ijpr}}{Fd_{ijpr}}\le n_iTH\quad\forall i\in I\tag{35}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{r=1}^{R}\frac{d_{ijpr}}{Fd_{ijpr}}\le n_jTH\quad\forall j\in J\tag{36}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{r=1}^{R}\left(d_{ijpr}+X_{ijpr}Vm_{ijpr}\right)Y_{rl}\leq Fpmaxl_{l}TH \quad \forall l\in L \tag{37}$$

$$\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{r=1}^{R}\frac{d_{ijpr}}{Fc_{ijpr}}\leq n_{j}TH \quad \forall j\in J \tag{38}$$

$$d_{ijpr}-X_{ijpr}Q_{ijpr}=0 \quad \forall i\in I; j\in J; p\in P; r\in R \tag{39}$$

$$d_{ijpr}\geq 0 \quad \forall i\in I; j\in J; p\in P; r\in R \tag{40}$$

$$0\leq If_{ip}\leq CAPW_{ip} \quad \forall i\in I; p\in P \tag{41}$$

$$0\leq If_{jp}\leq CAPW_{jp} \quad \forall j\in J; p\in P \tag{42}$$

$$X_{ijpr}\in Z^{+} \quad \forall i\in I; j\in J; p\in P; r\in R \tag{43}$$

5. Computational results

The proposed MINLP model (Eq. 8 to Eq. 27) is used to minimize the costs of the three supply chains of gasoline described in Section 3 and illustrated in Fig 2, Fig 3, and Fig 4, since the three supply chains of gasoline must solve the same decision variables to optimally operate pipelines and storage terminals.

5.1 Case study

In this section, as a real-life study case, a small network of Mexico's gasoline supply chain through pipeline is optimized (Fig 7) under the three supply chains of gasoline described in Section 3: gasoline supply chain before the 2013 Mexican Constitutional Reform (Fig 2), gasoline supply chain according with the 2013 Mexican Constitutional Reform (Fig 3), and under the proposed gasoline supply chain based on product standardization with postponement strategy (Fig 4). The results are compared in Section 5.2 to conclude whether the proposed strategy represents a solution to the supply chain problem presented in the introduction of this paper. The proposed supply chain solves the problem under study only whether the total costs of Mexico's gasoline supply chain managed under the proposed gasoline supply chain based on product standardization with postponement strategy (Fig 4) is cheaper than the total costs of Mexico's gasoline supply chain before the 2013 Mexican Constitutional Reform (Fig 2) and the total costs of Mexico's gasoline supply chain according with the 2013 Mexican Constitutional Reform (Fig 3).

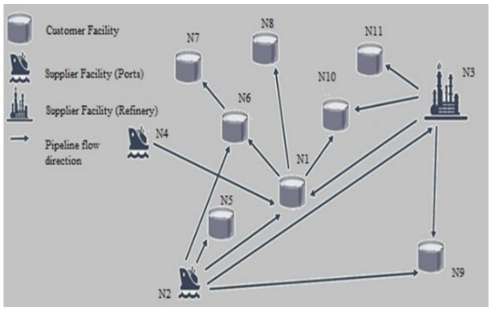

Fig. 7. Case study, supply chain pipeline network of gasoline

Six scenarios are proposed. The same data is used to run these scenarios as follows:

- In scenario 1, the small network of Mexico's gasoline supply chain through pipeline is operated according with the gasoline supply chain before the 2013 Mexican Constitutional Reform (Fig 2). One oil company simultaneously distributes two different types of gasoline (A and B). This is a multiproduct scenario where pipelines and storage terminals are used by only one oil company. In this scenario, the oil company distributes and sells gasoline A and gasoline B, midgrade is sold as gasoline A. As it has been explained through the paper, midgrade gasoline is created when an oil company uses its pipelines and storage terminals to distribute different types of gasolines. In this scenario, operation costs do not increase because mid-grade gasoline is sold as another type of gasoline, in this case, as gasoline A which is cheaper than gasoline B. Therefore, the Cm_{ijpr} is equal to zero, and the opportunity cost is calculated as the difference between both gasoline prices (β_p-β_{mdg}).

- In scenario 2, the small network of Mexico's gasoline supply chain through pipeline is operated according with the gasoline supply chain proposed in the 2013 Mexican Constitutional Reform (Fig 3). Two oil companies distribute two different types of gasoline (A and B). This is a multiproduct and a multi company scenario, where the same pipelines and storage terminals are used by two oil companies. As it has been explained, in this scenario, midgrade gasoline cannot be sold as another type of gasoline, it must be transported to a refinery to apply a transmix refining process, hence $Cm_{ijpr} \geq 0$. In this paper, we assume an opportunity cost equal to zero (β_p-β_{mdg}=0), but we must recognize that the quantities of gasolines are not fully recover during the transmix refining process.

- In scenario 3, the small network of Mexico's gasoline supply chain through pipeline is operated according with the gasoline supply chain proposed in this paper (gasoline supply chain based on product standardization with postponement strategy) (Fig 4). Two oil companies distribute two different types of gasoline (A and B). This is a multiproduct and a multi company scenario, where the same pipelines and storage terminals are used by two oil companies who distribute standard gasoline and transform it to gasoline A and gasoline B downstream the supply chain of gasoline at their PSTs. Midgrade gasoline is created because standard gasolines mix, but since these gasolines are similar in quality and ready to be additivated, a transmix process is not needed, hence, Cm_{ijpr} variables are equal to zero, we assume an opportunity cost equal to zero (β_p-β_{mdg}=0), and the lead times (L_{jp}) as the lead-time standard deviations (σ_{Ljp}) are minimized because oil companies can swap standard gasoline between them anytime. However, it is unknown exactly how much lead times (L_{jp}) as the lead-time standard deviations (σ_{Ljp}) can be minimized, hence two sub scenarios are analyzed: in scenario 3.1 the values of these parameters stay, at their maximum possible values, equal to scenarios 1 and 2; and in scenario 3.2 the values of these parameters are equal to zero, at their minimum possible values.

- Scenario 4 is the same as scenario 1, but with three gasolines (A, B and C). One oil company simultaneously distributes three different types of gasoline (A, B and C).

- Scenario 5 is the same as scenario 2, but with three gasolines (A, B and C). Three oil companies distribute three different types of gasoline (A, B and C). This is a multiproduct and multi company scenario, where the same pipelines and storage terminals are used by three oil companies.

- Scenario 6 is the same as scenario 3, but with three gasolines (A, B, and C). This is a multiproduct and a multi company scenario, where the same pipelines and storage terminals are used by three oil companies who distribute standard gasoline and transform it to gasoline A, B, and C downstream the supply chain of gasoline at their PSTs. However, it is unknown exactly how much lead times (L_{jp}) as the lead-time standard deviations (σ_{Ljp}) can be minimized, hence two sub scenarios are analyzed: in scenario 6.1 the values of these parameters stay, at their maximum possible values, equal to scenarios 4 and 5; and in scenario 6.2 the values of these parameters are equal to zero, at their minimum possible values.

Table Appendix A.1 and Table Appendix A.2 present the data for the study case, the names of the locations and source of data are confidential and therefore not shown. The currency is the Mexican peso (MXN) (1 MXN is approximately equal to 0.05 usd) and the measure of volume is in barrels of oil (Bbl) rather than m^3 because Bbl is the industry standard measure, and the results are more meaningful and visible (1 Bbl is equal to 0.1589873 m^3). The cycle service level inventory policy (1-α_{jp}) is 0.95, the probability of a stock out occurring (α_{jp}) is 0.05, the initial inventory (Io_{jp}) is zero for all customers and for all gasoline types, and 10 storage tanks are available at all facilities. Table Appendix A.1 shows the supplier facility offers, customer facility demands, the data needed to calculate the inventory costs, inventory levels, and the costs of ordering while Table Appendix A.2 shows the routes between suppliers and customer facilities, the data needed to calculate the cost of transportation, the total cost of interfaces, the facilities that are connected through a pipeline, and the physical characteristics of the pipeline network. It also presents the average amount of mid-grade gasoline that is blended when different gasolines are distributed through each pipeline, the maximum flow capacity given for each pipeline, average lead times, and lead times standard deviations.

The cost of an additivation machine is approximately $910,351.46 MXN with an additivation capacity of 12,000 [Bbl/day]. The required amount of fuel additive is between 100 [ppm] or 0.1 [kg/m^3] and 631 [ppm] or 0.631 [kg/m^3] according with the Mexican norm NOM-016-CRE-2016 (ENE, 2016) and is consistent with the literature (Theaker, 2011; Groysman, 2014; Senthil, Arunan, Silambarasan, Pranesh, & Mebin, 2015). In this paper, 0.631 [kg/m3] is used as the required amount of fuel additive for the scenarios under study, because this is the maximum amount of additive that could be required, so the maximum possible cost of transportation is considered. Table Appendix A.3 shows the amount of additive required for producing each type of gasoline at each PST. Table Appendix A.4 shows the number of additivation machines, and the investment needed at each PST depending on the demand per gasoline type. In scenarios 3.1 and 3.2, the total investment required is 32.77 million MXN. In scenarios 6.1 and 6.2, the total investment required is 47.79 million MXN.

In this paper, the annual cost for transportation of additives is calculated with the capacitated vehicle routing problem (CVRP) model. Table Appendix A.5. shows the cost of transportation per shipment using a tank truck with a capacity of 30 cubic meters. Data are calculated using the real road distance between the facilities shown in Fig 7 and the cost of transportation reported by Ramos (2019). Table Appendix A.6 shows the average travelling time windows by road. The solution of the CVRP model calculates the annual cost of transporting additives is 5.42 million of MXN in the gasoline supply chain of scenarios 3.1 and 3.2, and 6.87 million MXN in the gasoline supply chain of scenarios 6.1 and 6.2.

5.2 Case study computing results and discussion

Table 2 and Table 3 show the results of the application of the MINLP model to optimize Mexico´s gasoline supply chain. The results of Table 2 show that in the gasoline supply chain of scenario 1, the operation cost (OPEC) is 4.97%, the purchase cost (PC) is 95.00%, and the opportunity cost (OPOC) is 0.03% from its total cost (TC); in the gasoline supply chain of scenario 2, the OPEC is 6.29%, the PC is 93.71%, and the OPOC is 0.00% from its TC; in the gasoline supply chain of scenario 3.1, the OPEC is 5.04%, the PC is 94.96%, and the OPOC is 0.00% from its TC; in the gasoline supply chain of scenario 3.2, the OPEC is 2.12%, the PC is 97.98%, and the OPOC is 0.00% from its TC; in the gasoline supply chain of scenario 4, the OPEC is 4.69%, the PC is 95.26%, and the OPOC is 0.05% of its TC; in the gasoline supply chain of scenario 5, the OPEC is 6.00%, the PC is 94.00%, and the OPOC is 0.00% from its TC; in the gasoline supply chain of scenario 6.1 the OPEC is 4.80%, the PC is 95.20%, and the OPOC is 0.00% from its TC; finally, in the gasoline supply chain of scenario 6.2, the OPEC is 2.14%, the PC is 97.86%, and the OPOC is 0.00% from its TC. These results indicate that, in the three supply chains of gasoline under study, the most expensive cost is PC followed by the OPEC, and the OPOC is irrelevant. It is important to mention that OPOC is greater than zero in the gasoline supply chain of scenarios 1 and 4 because midgrade is sold as gasoline A and OPOC is calculated as the difference between the prices of the blended gasolines (β_p-β_{mdg}). In the gasoline supply chain of scenarios 2 and 5, midgrade gasoline is shipped to a refinery to perform a transmix refining process, therefore, it is assumed that OPOC is not created; and in the gasoline supply chain of scenarios 3.1, 3.2, 6.1 and 6.2, midgrade gasoline is not created, hence, OPOC is not created.

On one hand, in Table 2, the TC of the gasoline supply chain of scenario 2 is 1.20% bigger than the TC of the gasoline supply chain of scenario 1, which means the gasoline supply chain of scenario 2 is 2555.01 million of MXN more expensive than the gasoline supply chain of scenario 1; and the gasoline supply chain of scenario 5 is 3212.64 million of MXN more expensive than the gasoline supply chain of scenario 4. These results prove that a supply chain problem is created when oil companies share pipelines and storage terminals, located at refineries and ports of entry for import, for the sequential distribution of different types of gasoline, because the application of this gasoline supply chain increases the TC rather than decreases it. On the other hand, in Table 2, the TC of the gasoline supply chain of scenarios 3.1 and 3.2 are 1.89% and 4.82% cheaper than the TC of the gasoline supply chain of scenario 1, which means the supply chain of gasoline proposed in this paper, modeled in scenarios 3.1 and 3.2, is 3969.56 and 10111.73 million of MXN cheaper than the gasoline supply chain of scenario 1 without counting the 32.77 million of MXN investment required by the proposed supply chain of gasoline to buy the number of additivation machines needed at each oil companies PSTs, and the additives cost of transportation estimated in 5.42 million of MXN; whilst, the supply chain of gasoline proposed in this paper, modeled in scenario 6.1 and 6.2, is 8021.91 and 15124.58 millions of MXN cheaper than the gasoline supply chain of scenario 4, without counting the 47.79 million of MXN investment required by the proposed supply chain of gasoline to buy the number of additivation machines needed at each oil companies PSTs, and the additives cost of transportation estimated in 6.87 millions of MXN. These results show that the investment required by the proposed supply chain of gasoline to buy the number of additivation machines, and the additives annual cost of transportation are completely irrelevant. These results prove that the proposed supply chain of gasoline, based in the supply chain strategy of product standardization for distribution, the supply chain management principle of collaboration, and in the supply chain strategy of postponement minimizes the TC of all the oil companies that share pipelines and storage terminals, located at refineries and ports of entry for import, to distribute different types of gasoline. More important, the results shown in Table 2 demonstrate that the supply chain of gasoline proposed in this paper is the cheapest, it is viable, and allows multiple oil companies share pipelines and storage terminals to simultaneously distribute different types of gasoline, as the 2013 Mexican energy reform dictates. The results also demonstrate that the supply chain of gasoline proposed in this paper solves the supply chain problem presented in this paper. It is important to acknowledge that even when the minimization of TC could seem to be minimal (less than 7% of TC in the best scenario) in monetary terms the percentage of savings is enormous.

Table 2. Case study total cost, operation cost, purchase cost, and opportunity cost

Scenario	TC [MXN]	OPEC [MXN]	PC [MXN]	OPOC [MXN]
1	209,723,061,203.81	10,430,152,376.00	199,233,732,138.64	59,176,689.17
2	212,278,067,463.08	13,351,646,212.55	198,926,421,250.53	0.00
3.1	205,753,496,228.30	10,373,650,054.02	195,379,846,174.28	0.00
3.2	199,611,331,950.42	4,231,485,776.15	195,379,846,174.28	0.00
4	269,754,983,259.71	12,643,203,130.41	256,973,919,835.07	137,860,294.23
5	272,967,625,038.54	16,382,121,487.73	256,585,503,550.82	0.00
6.1	261,733,077,316.33	12,550,301,365.20	249,182,775,951.13	0.00
6.2	254,630,407,826.23	5,447,631,875.10	249,182,775,951.13	0.00

One advantage of the proposed supply chain of gasoline is the possibility of applying a systematic cooperative reciprocal barter strategy, also known as swap collaboration, where companies can swap their stockpiles of standard gasoline between themselves. The values of L_{jp} and σ_{Ljp} are zero in the proposed supply chain of gasoline applied in scenarios 3.2 and 6.2 to analyze the advantage of applying a swap collaboration strategy where oil companies can get standard gasoline from CSTs any time, because standard gasoline continuously flows through the pipeline without interruption. In other words, in this gasoline supply chain, oil companies do not need to wait for their gasoline batches what happens only if oil companies swap standard gasoline, otherwise L_{jp} and σ_{Ljp} must be greater. Contrary, the proposed supply chain of gasoline is analyzed in scenarios 3.1 and 6.1 without applying a swap collaboration strategy because oil companies must wait the lead time to get standard gasoline from CSTs. The comparison of the results of these supply chain of gasoline highlights the advantage of the proposed supply chain of gasoline of being able to apply a swap collaboration strategy. These results demonstrate that huge savings can be achieved when oil companies swap standard gasoline at the CSTs, because the TC of the gasoline supply chain of scenario 3.1 is 6142.16 million of MXN (3.08%) more expensive than the TC of the gasoline supply chain of scenario 3.2, and the TC of the gasoline supply chain of scenario 6.1 is 7102.67 million of MXN more expensive than the TC of the gasoline supply chain of scenario 6.2 (Table 2).

In Table 2, the OPEC of the gasoline supply chain of scenario 2 is 2921.49 million of MXN (28.01%) more expensive than the OPEC of the gasoline supply chain of scenario 1 and the OPEC of the gasoline supply chain of scenario 5 is 3738.92 million of MXN (29.57%) more expensive than the OPEC of the gasoline supply chain of scenario 4. These results demonstrate that the supply chain of gasoline of scenarios 2 and 5 increases OPEC. Contrary, the PC of the gasoline supply chain of scenario 2 is 307.3 million of MXN (0.15%) smaller than the PC of the gasoline supply chain of scenario 1 and the PC of the gasoline supply chain of scenario 5 is 388.42 million of MXN (0.15%) smaller than the PC of the gasoline supply chain of scenario 4, whilst the OPOC of the gasoline supply chain of scenario 2 is 59.18 million of MXN smaller than the PC of the gasoline supply chain of scenario 1; and the OPOC of the gasoline supply chain of scenario 5 is 137.86 million of MXN smaller than the PC of the gasoline supply chain of scenario 4. These results demonstrate that the supply chain of gasoline of scenarios 2 and 5 decreases PC and OPOC. These results confirm that oil companies should not share pipelines and storage terminals, located at refineries and ports of entry for import, for the sequential distribution of different types of gasoline, because the savings achieved in PC and OPCO are very low in comparison with the increase in OPEC.

Table 3 shows the costs that form the OPEC. In general, the results of Table 3 show that: in the gasoline supply chain of scenario 1, the transportation cost (TRAC) is 16.92%, the ordering cost (OC) is less than 0.00%, the transmix refining process cost (MGC) is 0.00%, and the inventory cost (HC) is 83.08% from its OPEC; in the gasoline supply chain of scenario 2, the TRAC is 13.21%, the OC is less than 0.00%, the MGC is 9.94%, and the HC is 76.85% from its OPEC; in the gasoline supply chain of scenario 3.1, the TRAC is 17.02%, the OC is less than 0.00%, the MGC is 0.00%, and the HC is 82.98% from its OPEC; in the gasoline supply chain of scenario 3.2, the TRAC is 41.72%, the OC is less than 0.00%, the MGC is 0.00%, and the HC is 58.28% from its OPEC; in the gasoline supply chain of scenario 4, the TRAC is 18.00%, the OC is less than 0.00%, the MGC is 0.00%, and the HC is 82.00% from its OPEC; in the gasoline supply chain of scenario 5, the TRAC is 13.88%, the OC is less than 0.00%, the MGC is 10.47%, and the HC is 75.65% from its OPEC; in the gasoline supply chain of scenario 6.2, the TRAC is 18.14%, the OC is less than 0.00%, the MGC is 0.00%, and the HC is 81.86% from its OPEC; and in the gasoline supply chain of scenario 6.2, the TRAC is 41.78%, the OC is less than 0.00%, the MGC is 0.00%, and the HC is 58.22% from its OPEC. These results indicate that, in the three gasoline supply chains under study, HC is the most expensive OPEC follow by TRAC, and OC is irrelevant. MGC is zero in the gasoline supply chain of scenarios 1 and 4 because it is sold as gasoline A, MGC is zero in the supply chain of gasoline proposed in this paper because midgrade gasoline is not created, this gasoline supply chain is applied in scenarios 3.1, 3.2, 6.1 and 6.2. MGC is greater than zero in the gasoline supply chain of scenarios 2 and 5 because midgrade gasoline must be shipped to a refinery to perform a transmix refining process.

Table 3. Case study transportation cost, ordering cost, interface cost, and inventory cost

Scenario	TRAC [MXN]	OC [MXN]	MGC [MXN]	HC [MXN]
1	1,764,500,687.82	82,062.07	0.00	8,665,569,626.11
2	1,763,318,582.93	67,022.30	1,327,519,556.48	10,260,741,050.84
3.1	1,765,436,853.83	82,590.12	0.00	8,608,130,610.07
3.2	1,765,436,853.83	82,590.12	0.00	2,465,966,332.19
4	2,276,054,935.88	103,183.94	0.00	10,367,045,010.59
5	2,273,331,545.37	84,047.39	1,715,770,998.10	12,392,934,896.87
6.1	2,276,074,225.77	104,186.44	0.00	10,274,122,952.99
6.2	2,276,074,225.77	104,186.44	0.00	3,171,453,462.89

The gasoline supply chain of scenarios 2 and 5 achieves cheaper TRAC and OC than the gasoline supply chain of scenarios 1 and 4. However, the savings are irrelevant because in the gasoline supply chain of scenarios 2 and 5, TRAC are 1.18 (0.07%) and 2.72 (0.12%) millions of MXN and OC are 15039.77 (22.44%) and 528.05 (0.64%) MXN cheaper than TRAC and OC of the gasoline supply chain of scenarios 1 and 4 respectively; contrary, in the gasoline supply chain of scenarios 2 and 5, MGC are 1327.52 and 1715.77 millions of MXN and HC are 1595.17 (18.41%) and 2025.89 (19.54%) millions of MXN more expensive than MGC and HC of the gasoline supply chain of scenarios 1 and 4 respectively. These results confirm that the production of midgrade gasoline increases the MGC and the HC of the supply chain of gasoline when oil companies share pipelines and storage terminals, located at refineries and ports of entry for import, to simultaneously distribute and store different types of gasoline creating a supply chain problem that increase costs, even if it is assumed that midgrade gasoline could be bought by one oil company (the distributor for example) to avoid the total cost of interfaces (MGC equal zero) the gasoline supply chain costs increase. Hence, the results obtained in this paper and shown in Table 3 demonstrate that the supply chain of gasoline proposed in the 2013 Mexican Energy Reform is expensive and therefore it is inviable.

In the gasoline supply chain of scenario 1, TRAC and OC are 936166.01 (0.05%) and 528.05 (0.64%) MXN cheaper than in the gasoline supply chain of scenarios 3.1 and 3.2; and in the gasoline supply chain of scenario 4, TRAC and OC are 19289.98 (0.00%) and 1002.50 (0.97%) MXN cheaper than in the gasoline supply chain of scenarios 6.1 and 6.2. However, these savings are irrelevant in comparison with the increase in HC because this cost is 57.44 (0.66%) millions of MXN and 6199.60 (71.54%) millions of MXN more expensive in the gasoline supply chain of scenario 1 than in the gasoline supply chain of scenario 3.1 (without swap collaboration) and scenario 3.2 (swap collaboration) respectively; and HC is 92.92 (0.90%) millions of MXN and 7195.59 (69.41%) millions of MXN more expensive in the gasoline supply chain of scenario 4 than in the gasoline supply chain of scenario 6.1 (without swap collaboration) and scenario 6.2 (swap collaboration) respectively. These results indicate that the main advantage of the proposed supply chain of gasoline is to minimize inventory levels. The minimum TC is achieved with the proposed supply chain of gasoline with a swap collaboration strategy because TC is 6142.16 (2.99%) millions of MXN more expensive in the gasoline supply chain of scenario 3.1 than in the gasoline supply chain of scenario 3.2; and TC is 7102.67 (2.71%) millions of MXN more expensive in the gasoline supply chain of scenario 6.1 than in the gasoline supply chain of scenario 6.2. Hence, the results obtained in this paper and shown in Table 3 demonstrate that the supply chain of gasoline proposed in this paper is the cheapest, it is viable, and allows multiple oil companies share pipelines and storage terminals to simultaneously distribute different types of gasoline as the 2013 Mexican Energy Reform dictates.

6. Conclusions

This paper analyzes the viability of the supply chain of gasoline proposed in the Mexican energy reform enacted in 2013. The main goal of this reform is to lower gasoline prices to consumers by enhancing competition between oil companies and finishing the state-owned company monopoly. To do so, a multi-product pipeline inventory-transport problem with stochastic demand and variable lead time (MINLP) is developed, together with a methodology that calculates the global optimum solution. The proposed MINLP is used to optimize three supply chain of gasoline: the state-owned company distributes different types of gasoline (Mexican supply chain of gasoline before the reform), the supply chain of gasoline proposed in the reform, and the supply chain of gasoline proposed in this paper. The optimization of these supply chain of gasolines allows to compare the minimum total cost that will be transferred to the consumer increasing gasoline prices, concluding which of these supply chains of gasolines achieves cheaper costs giving the possibility of lower gasoline prices. The results are valid because the proposed MINLP models the supply chain of gasoline problem with the aim of minimizing transportation costs, inventory costs, and transmix refining process costs of the supply chain of gasoline of one or more one oil company from common storage terminals (CSTs) located at the beginning of pipelines to CSTs located at the end of pipelines. The global optimum methodology developed in this paper to solve the MINLP assures the calculation of the minimum total cost.

The results of this paper demonstrate that a supply chain problem is created when multiple oil companies share pipelines and storage terminals to simultaneously distribute different types of gasoline, as the Mexican energy reform dictates, because costs increase due to the production of midgrade gasoline created each time two different types of gasoline are sequentially shipped through the same pipeline. Therefore, the supply chain of gasoline proposed in the 2013 Mexican energy reform is inviable because prices cannot fall when costs increase, concluding that oil companies should not share pipelines and storage terminals to sequentially distribute and store more than one type of gasoline. The results of the optimization of the supply chain of gasoline before the reform shows that the production of midgrade gasoline is easily solved when the pipeline network is used by a single company because mid-grade gasoline can be sold as another type of gasoline, which is possible because mid-grade gasoline is the result of the combination of two gasolines owned by the same oil company. But this solution does not work when mid-grade gasoline is the result of the combination of gasolines owned by different oil companies. In this case, the optimization of the supply chain of gasoline proposed in the reform shows that the solution to transport mid-grade gasoline to a refinery to apply a transmix refining process is expensive, and even if supposing that midgrade gasoline could be bought by one oil company (the distributor for example) to avoid the total cost of interfaces (MGC equal zero), the proposed supply chain of gasoline in the reform still the most expensive and therefore the results confirm it is inviable. Contrary, the optimization of the supply chain of gasoline proposed in this paper proves that the best solution is to convince oil companies to collaborate and distribute a standard gasoline performing the additivation process of gasoline at oil companies PSTs near customers applying a supply chain postponement strategy, rather than at their refineries, because it allows them to share pipelines and storage terminals to simultaneously distribute different types of gasoline maximizing infrastructure capacities and minimizing costs. Therefore, the supply chain of gasoline proposed in this paper allows oil companies to share pipelines and storage terminals to simultaneously distribute different types of gasoline, as the Mexican Energy Reform dictates, but at minimum cost. The proposed supply chain of gasoline gives the state owned and private oil companies get economic benefits that could be reflected in lowering gasoline prices in an economic competition environment.

The supply chain of gasoline proposed in this paper takes advantage of economies of scale through product standardization. It achieves logistical and cost advantages because it has the capacity of distributing an unlimited number of different types of gasoline at the lowest possible cost by aggregating the demand for all the different types of gasoline to one demand of standard gasoline and allowing a high level of flexibility. The proposed supply chain solves the supply chain problem under study because the production of gasoline is finished at oil companies' PSTs downstream of the gasoline supply chain at the lowest possible cost. This is because the investment required by the proposed supply chain of gasoline to buy the number of additivation machines, and the additives annual cost of transportation are completely irrelevant when compared with the savings achieved in OPEC, PC and OPOC. Logistical advantages are achieved because storage and transport infrastructure operate efficiently causing lead times, batch sizes, and inventory levels to fall considerably. Lead times are reduced to a minimum because oil companies can apply a systematic cooperative reciprocal barter strategy swapping their stockpiles of standard gasoline between themselves, so standard gasoline continuously flows through the pipeline network, ensuring the amount of gasoline distributed through pipelines is enough to satisfy the demand of all markets, whilst minimizing shortfalls, loss of sales, and dissatisfied customers. The results also prove that the proposed supply chain of gasoline is more agile than the supply chain of gasoline operating before the reform, mainly because it responds faster to customer demand as lead times are the shortest possible. The sizes of the batches are also minimized because oil companies can pick up standard gasoline at any time from the CSTs located at the end of pipelines allowing oil companies to manage small inventory levels of different types of gasolines at their PSTs minimizing HC which is the most expensive OPEC following by TRAC, and OC is irrelevant. Hence, the main advantage of the proposed supply chain of gasoline is the minimization of HC. The main disadvantages of the supply chain of gasoline proposed in this paper is the fact that it requires all the oil companies to distribute standard gasoline and to share its information in a daily basis about the amount of standard gasoline they pushed and picked up from the distributor pipeline network, otherwise, whether one of them is not willing to collaborate, midgrade gasoline is going to be created and gasoline supply chain costs would increase for all.

One future research includes studying the effects of simultaneous cooperation and competition (coopetition) among oil companies as it is raised in the supply chain of gasoline proposed in this paper applying cooperative game theory. The goal is to develop a mathematical model that allows to study oil companies' internal structural changes due to cooperation among them because their profit functions will change due to the level of cooperation level, so it is important to calculate the right level of cooperation. Another future research is to study the effects of swapping in lead time. The goal is to design a methodology that allows the effective coordination of swaps between the oil companies as it is raised in the supply chain of gasoline proposed in this paper. Such methodology requires the development of a mathematical model that captures the complexity in swap transactions between oil companies. This mathematical model is important to understand the effects of swapping in lead times.

7. References

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