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NATURAL GAS SUPPLY CHAIN: A SYSTEM AND PERFORMANCE ORIENTED APPROACH

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Thesis Introduction

Global energy consumption has been increasing in recent years. Among the main global energy sources, natural gas stands out. It presents benefits from diverse points of view, low emissions for the environment, low price for the consumers, lower cost and simplicity in the supply. That is why, within the global policies of emission reduction, natural gas is considered the source of transition energy between fossil fuels and clean, renewable and sustainable sources of energy.

Considering that natural gas is a non-renewable resource, it presents a significant and progressive reduction in reserves in some regions worldwide, but with ample possibilities for the discovery of new reserves and transport from regions with greater availability of this resource. This reduction is not different to the Colombian case, where there has even been a reduction in the national production in contrast to the accelerated increase in demand from the various consumer sectors, which exposes the nation to a situation of shortages of this resource in the next years, this being even more critical, since power generation in Colombia highly depends on hydroelectricity, making natural gas to emerge as an attractive backup energy production of electricity through thermoelectric generation, in the occurrence of climatic phenomena of drought and decrease in river levels.

Research carried out regarding the supply of natural gas in some regions of the world and even in Colombia, account for the analysis of elements such as price, environmental impact, reliability and essentially using optimization model, but nevertheless, these investigations do not consider the integration of both public and private actors from the perspective of Supply Chain Management (SCM), which affects the overall performance and results achieved by the system.

In the supply of natural gas in Colombia, various actors intervene to extract, produce and transport, which interact to guarantee the supply of the resource. Therefore, by framing these actors according to an integrated perspective and analysing the outcomes of public policies through the use of dynamic simulation models, it is possible to identify which of these policies may produce the greatest impact in the future in terms of generating the necessary capacity and reliability in the supply, that is useful for stakeholders and decision makers.

In this dissertation, the supply of natural gas for the Colombian case is studied, with a focus on the analysis of the integration and interaction of the actors involved in its Supply Chain Management, considering the necessary policies that guarantee the reliability of the national system, through models that combine Systems Dynamics Simulation (SD) and Dynamic Performance Management (DPM). As emerged by the analysis of the prevailing literature, the foregoing seeking to contribute to the research on managing natural gas supply through dynamic models has not been exhaustively addressed in previous research.

This thesis is formed by three chapters containing each a research article. The first chapter analyses in depth previous research regarding natural gas supply and the use of systems dynamics, then, it presents a scenarios analysis to study the effect of variables such as percentage of reliability and time of generation of capacity in transportation of natural gas supply. This allows decision makers to establish priorities in the allocation of resources for the implementation of infrastructure projects. In the second chapter, more entities are involved in the supply chain of natural gas, such as reserves, production, transport and demand, and an analysis of the effect of the price at the mouth of the well on the supply and demand of production and the price to the consumer on the supply and demand of transport is carried out. Such an analysis enables the identification of stabilization values for these prices and the levels of capacity in construction and existing one by the actors with respect to the natural gas demand projections. Eventually, in the third chapter, based on the findings of the previous chapters, the Dynamic Performance Management (DPM) methodology is applied to evaluate the impact of public policies aimed at enhancing reliability and the development of necessary capacity in the actors of the chain of natural gas supply, guaranteeing the uninterrupted provision of this resource.

Chapter 1. Demand, transport and production model. Effects of supply capacity on natural gas demand

Chapter abstract. In this chapter, a system dynamics model of the natural gas supply chain in Colombia is developed. The model incorporates demand, transport and production of natural gas in an integrated manner. It also includes the effects of natural gas price based on the levels demand and supply. The simulations of the model are carried out against five scenarios in which variables of coverage and capacity building of the supply chain are modified. This case study presents the dynamics of the aforementioned variables over time, allowing decision makers and stakeholders to identify delays in meeting the demand according to the allocation of natural gas, as a support in the formulation of public policies oriented to implement infrastructure projects that may mitigate shortage risks.

Chapter keywords: Supply Demand, Natural Gas, Systems Dynamics, Modeling.

1.1 Introduction

1.1.1 Worldwide and Colombia natural gas demand and supply

As an essential element of the green growth strategy of the Organization for Economic Cooperation and Development (OECD), the development of a mix or a larger portfolio of renewable energy sources is proposed [1], within which natural gas - despite being part of the non-renewable sources of energy - is currently regarded as a “bridge fuel” between the sources of fossil energy and the energy sources that contribute to the sustainable growth of global economies, considering also social development and reduction of environmental impact, lower cost of implementation and lower levels of pollution, especially in sectors experiencing constant growth in demand such as the transport sector and energy generation [2].

The reserves of natural gas worldwide present an increase of 18.2% between 2007 and 2017 [3]. At the end of 2017, these reserves reached 193.4 Trillion Cubic Meters [TCM], from which the regional participation was, 40.9 % in the Middle East, 30.6%, in the Commonwealth of Independent States (CIS), 10.0% in Asia Pacific, 7.1% in Africa, 5.6% in North America, 4.2% in South and 1.6% in Central America and Europe. For its part, the production of natural gas worldwide between 2007 and 2017 increased from 2.94 to 3.68 [TCM] which represents an increase of 25.12%, with a participation for this last year by region: North America 25.9%, CIS 22.2%, Middle East 17.9%, Asia Pacific 16.5%, Europe 6.6% and Africa 6.1%, South and Central America 4.9% [3]. In contrast, world consumption between 2007 and 2017 went from 2.96 to 3.67 [TCM], which represents an increase of 24.08% in this period. The share of consumption by region for the year 2017 was North America 25.7%, Asia Pacific 21.0%, CIS 15.7%, Middle East 14.6%, Europe 14.5%, South and Central America 4.7% and Africa 3.9% [3].

Between 2010 and 2016, natural gas reserves in Colombia showed an average annual change of –6%, going from 7.1 to 5.3 Trillion Cubic Feet. On the other hand, production showed a critical decrease between 2014 and 2017, with an average decrease of –5.52%, passing in 2014 from 1153 to 955 in 2017 Giga BTU per day [GBTUD]. The foregoing is contrasted with the demand between 2009 and 2015 that has presented an average increase of 3.4%, thus showing in general terms an imbalance between supply and demand of natural gas in the country [4].

As an indicator of reserve levels against the production of natural gas, the reserves-production ratio (R/P) is calculated as a dimensionless measure. This ratio on a global level went from 62 in 2007 to 51 in 2017, representing by region for this last year: Middle East 120, CIS 73, Africa 61, South and Central America 46, Asia Pacific 32, Europe 12 and North America 11 [3]. In the case of Colombia, the indicator moved from 18.1 in 2010 to 12.6 in 2017, estimating that it will reach 0.8 with the current reserves and the country capacity by the year 2030 [4].

The generation of electricity in Colombia depends on hydroelectric and thermal generation using natural gas and coal, reason why in 2016, 16,596 megawatts (MW) were generated, with a 70% share of water sources, 13% of natural gas and 8% of coal [5]. Colombia has been affected by a periodic climatic phenomenon event called "El Niño", which causes rains, very dry periods and consequently a reduction of water levels in rivers. This represents a dangerous risk due to the heavy dependence from hydroelectricity in the country, thus considering thermal generation by natural gas as a source of support during periods when this phenomenon occurs [4], given its lower environmental impacts and lower cost as opposed to the use of coal [6].

In addition, through the analysis of various natural gas supply and demand scenarios in the country, the Mining and Energy Planning Unit of Colombia (UPME) highlights the presence of deficit in the supply of the resource by February 2024, which indicates that the country needs to make prompt decisions in order to achieve supply security and reliability [7].

In accordance with the above, it is considered of great importance to study the timely supply of natural gas in Colombia, which contributes to government policies that point to the transition to clean energy sources and to generate reliability in the support of electric power, with a greater contribution to the environmental sustainability through the reduction of emissions, reduction of consumer prices, economic and competitive development of the country.

1.1.2 Literature review

The literature review is based on the most relevant research carried out from two perspectives: the modelling of natural gas supply chains and the application of the system dynamics methodology in the supply of natural gas.

1.1.1.1 Modeling natural gas supply chains

The software Tree of Science has been used for conducting the citations analysis. Such software performs narrative search, analysis of citation patterns (networks) and meta-analysis, classifying the articles in: classic articles (root), structural articles (trunk) and recent articles (leaves) [8].

Among the retrieved literature classics, the research carried out by Cafaro and Grossman [9] and by Gao and You [10] are highlighted in terms of the design and planning of resources in the shale gas supply chain, using mathematical models of optimization. The research of You and Wang [11] is also relevant in the study of the design and optimal planning of the supply chain of biomass-to-liquids (BTL) considering economic and environmental criteria through the application of a model of optimization.

In terms of structural articles, the review by Elia and Floudas [12] and by Gao and You [13] analyses the research and mathematical models applied to the performance and optimal design of energy supply chains (shale gas case in the latter), remarking the relevance of the geographical location of the facilities on the economic, environmental and social impact, in addition to the importance of optimization models in the study of energy systems. Research related to the design, planning and optimization of the shale gas supply chain network considering environmental aspects, are presented by Gao and You [14] and by Guerra et al. [15] in which optimization and simulation methods are applied. In the study of the planning at several levels (strategic, tactical and operational) of natural gas supply chain networks, it is worth considering the research of Hamedi et al. [16], Elia et al. [17], DeRosa and Allen [18] and Elia et al. [19] in which optimization models are mainly used to reduce costs and allocate resources for supply.

The most recent articles can be classified in those related to Bioenergetics, Liquefied Natural Gas (LNG), Shale Gas and Natural Gas. In the field of bioenergetics, the research of Pérez et al. [20], Jensen et al. [21], Ghelichi et al. [22] and Hoo et al. [23] are significant. There, the design and optimization of biomass, biogas, biodiesel and biomethane supply chain networks are studied, through economic and optimization models. Other research studies, such as Bekkering et al. [24], suggest the supply of Green gas as an alternative to natural gas for seasonal demands, using an optimization model. In the strategic planning process among the actors of the supply chain and in the design of strategies for the importation and assurance of the supply of Liquefied Natural Gas (LNG) applying comparative and optimization models, the research by Werner et al. [25], Geng et al. [26], Bittante et al. [27] and Sapkota et al. [28] are valuable. In the case of shale gas, there is research on supply chain planning, investment in infrastructure, allocation of consumed resources and reduction of environmental impact, such as Tan and Barton [29], Chebeir et al. [30], He et al. [31], [32] and Chen et al. [33], in which utility optimization models are used for stakeholders.

Specifically in the study of natural gas supply chains, the research of Dujak [34] is of great interest. The author presents a literature review for the effective use of the natural gas supply chain mapping. In understanding the emissions and environmental effects of the natural gas supply, Crow et al. [35] apply a Dynamic Upstream Gas Model and Balcombe [36] employing a probabilistic model. Using a Montecarlo model, Hauck et al. [37] studies the supply chain in which natural gas is used to generate electricity. In the research of Safarin et al. [38] and [39] the allocation of capacities and infrastructure in the supply of natural gas through optimization models is also analysed. Mikolajkova et al. [40], [41] present studies on the infrastructure for transportation and distribution of natural gas, while Malinowski [42] in the effects of the demand for helium supply chain, through mixed integer linear programming models.

As it is observed, the developed research regarding the problem of energy supply and especially of natural gas, is mostly done by means of optimization modelling applied to the supply chain. Through this research is proposed to address this problem through the system dynamics methodology.

1.1.1.2 System dynamics applied to the natural gas supply

System Dynamics (SD) has been used to explore the supply of natural gas. The extant research studies on this topic are shown below.

Among the main studies related to natural gas supply, it is worth mentioning the research contribution by Cai et al. [43]. The authors apply a system dynamics model to provide alternatives in helium production that is closely associated with future production of natural gas. North et al. [44] use an integrated model (system dynamics and agents) for the analysis of energy security, which provides a description of two alternative methods used to study conflicts in energy supply. Ponzo et al. [45] develop a model to understand the gas supply in Argentina. There, they discuss how regulation influences long-term supply in that country and also in neighboring countries, then they conclude with a discussion related to the evolution of gas markets.

Within the study of the energy market and natural gas, Bunn et al. [46] develop a model on the electricity market, in which a dominant electricity generator could retail in the electricity and gas markets, due to its size and capacity. Jingchun et al. [47] model the trend of supply and demand of natural gas in China under different scenarios between the years 1990 and 2050. In addition, they present a forecasting model of natural gas supply using system dynamics. Li et al. [48] also use a systems dynamics model that shows the growth of gas consumption in China, increasing from 89.5 million cubic meters in 2010 to 198.2 million cubic meters in 2020, so that it eventually reaches 340.7 billion cubic meters.

The systems dynamics methodology is useful supporting policy and decision-making processes. Olaya and Dyner [49] use an optimization and systems dynamics model in order to address the sustainability of the natural gas industry, identifying that the integration of modelling methodologies could be of great value for the formulation, understanding and evaluation of energy policies in the natural gas sector in Colombia. Chyong Chi et al. [50] propose a system dynamics model to investigate the factors influencing the long-term supply and demand of natural gas in the United Kingdom, determining the nature of the system's behaviour, as well as analysing the effectiveness of the different transition from self-sufficiency to long-term gas imports. Eker and Van Daalen [51] study the dynamics of biomethane production in the Netherlands by analysing the effects of subsidy policies, using a system dynamics model. Horschig et al. [52] build a simulation model using systems dynamics for the German energy market. The results of the baseline scenario show that, without R&D funding and incentive plans, the penetration into the country's market of Bio-Substitute Natural Gas is not achieved.

Some studies consider the environmental impact of energy supply. For instance, Bala [53] presents a computational model for energy and environment, in order to generate projections of the supply and demand of energy, evaluating the impact on global warming. Howells et al. [54] apply an optimization and system dynamics model that includes some economic interactions with the energy system, in the implementation of measures that impact on the reduction of emissions in the environment. Yücel and Van Daalen [55] use a simulation model based on agents and system dynamics under eight different scenarios, finding continuous domination of fossil fuels as an energy source, with a change in the use of natural gas to coal as a base case. Eker and Daalen [56] suggest a system dynamics model in which the results show that the objectives in terms of annual production volume, energy consumption and CO_2 emissions can be achieved in the Netherlands only in a small proportion of the future scenarios analysed.

In other research works more related to this chapter's aims, Becerra et al. [57] develop a system dynamic model for the natural gas demand and supply (production and transport) in Colombia, enabling to identify capacity levels to be developed considering changes in the implementation times and the coverage percentages (reliability) in the supply. Additionally, Becerra et al. [58] present a natural gas supply chain model, in which reserve, production, transport and demand sectors are involved, applying the Dynamic Performance Management (DPM) methodology [59] in order to analyse the relevant policies in terms of capacity generation for the supply of natural gas in the Colombian case. In a related research Becerra and Rodríguez [60] use the Analytic Hierarchy Process (AHP) to evaluate the selection of alternatives proposed by the national government for the supply of natural gas in Colombia.

Once the relevant literature has been reviewed, it is found that energy supply through systems dynamics has not been widely studied combining Supply Chain Management approach and System Dynamics approach, which is why this research contribute in a novel way to the assay of the effect of public policies for the reliable supply of natural gas.

This chapter is organized as follows: in the modelling section of the supply chain, the hypotheses of this research are presented, using causal diagrams and stock and flow structures. Subsequently, the variables and parameters used in the modelling are identified, as well as the verification and validation of the model developed. The results section analyses the behaviour of the system under five scenarios that combine variables upon which policy makers can intervene in the supply of natural gas in Colombia. Eventually, conclusions are presented summing up the main contributions of studying the supply of natural gas through the relationship among demand, transport and production.

1.2 Natural gas demand, transport and production model

1.2.1 Causal loop diagram for the demand, transport and production of natural gas

The dynamic hypothesis *Hi* considered for building the model is based on what was proposed by Whelan et al. [61] in the demand and supply model, Cárdenas et al. [62] in the analysis of policies for emissions mitigation, Sterman [63] in the supply chain modeling, and Becerra et al. [57], [58] in the assessment of public policies for the natural gas supply chain. This hypothesis can be observed graphically in Figure 1 and is explained below:

- H_1: The modelling of the supply of natural gas in Colombia considering the relationship demand, transport and production, allows observing the effect of the resources allocated in transport capacity, as opposed to supplying the demand of the national consumption sectors.

Figure 1 exhibits the main loops included in the model and is explained below:

- *Supply loop:* the increase in demand for natural gas causes an increase in the need for natural gas to be transported, which considers a percentage of safety stock that guarantees supply during the time required for capacity building. From the level of transport and the mentioned capacity expansion requirement, the transport margin is calculated. It influences the reduction of the suggested price to the consumer, which, when increased, also increases the price perceived by the consumer. This price generates an effect on the increase of the supply, based on the production capacity and therefore on the levels of gas produced. This produced gas, considering a delay in capacity building, increases the levels of natural gas transported.
- *Consumer price loop:* this loop is included in the supply feedback loop, from the transport margin to the price perceived by the consumer. An increase in this price generates the decrease in demand and the natural gas needed to be transported.

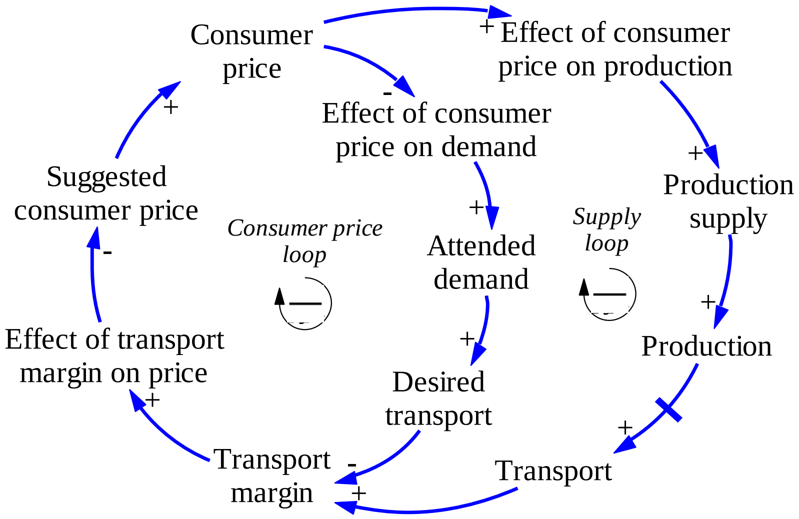


Figure 1. Causal loop diagram of the natural gas model

1.2.2 Stock and flow diagram for the demand, transport and production of natural gas

The stock and flow diagram developed from the causal diagram (see Figure 1), is based on the approach of Whelan et al. [61] through the representation of the supply and demand model, in relation to the demand of the consumer sectors, transport and supply of natural gas (see Figure 2). Additionally, the equations of the model developed through the software iThink can be observed in Appendix A.

Within the model of demand and supply of natural gas in Colombia, the main actors intervening in the supply are combined, as described below [64]:

- *Demand:* includes the industrial, domestic, refineries, compressed natural vehicle gas, petrochemical, electric and residential generation sectors. It considers the estimated population growth in Colombia.
- *Transportation:* represents the volume of distribution that is related to the National Transportation System (known in Spanish as SNT) and its interconnected networks.
- *Production:* considers the national production and disposal capacity of natural gas for transportation.

Within the design of the natural gas supply and demand model, four stock variables are considered, which represent changes in the natural gas levels from production to delivery to the final consumer. In these level variations, the demand of the previous link (actor), corresponds to the capacity requirements of the next link. Additionally, it is considered a variable of this type for the price to the consumer. All this is expressed in Giga Cubic Feet [GCF]. The first stock variable corresponds to the production level (*P*), which represents the result of the treatment that the plants make to the extracted natural gas so that it can be transported to the final consumer.

$$\frac{dP}{dt} = PSP - PS \qquad (1)$$

Where (*PSP*) represents the supply of natural gas from the production capacity of the supply system (*PC*) and the effect of the consumer price on production (*ECPP*), as shown in Figure 3.

$$PSP = PC \times ECPP \qquad (2)$$

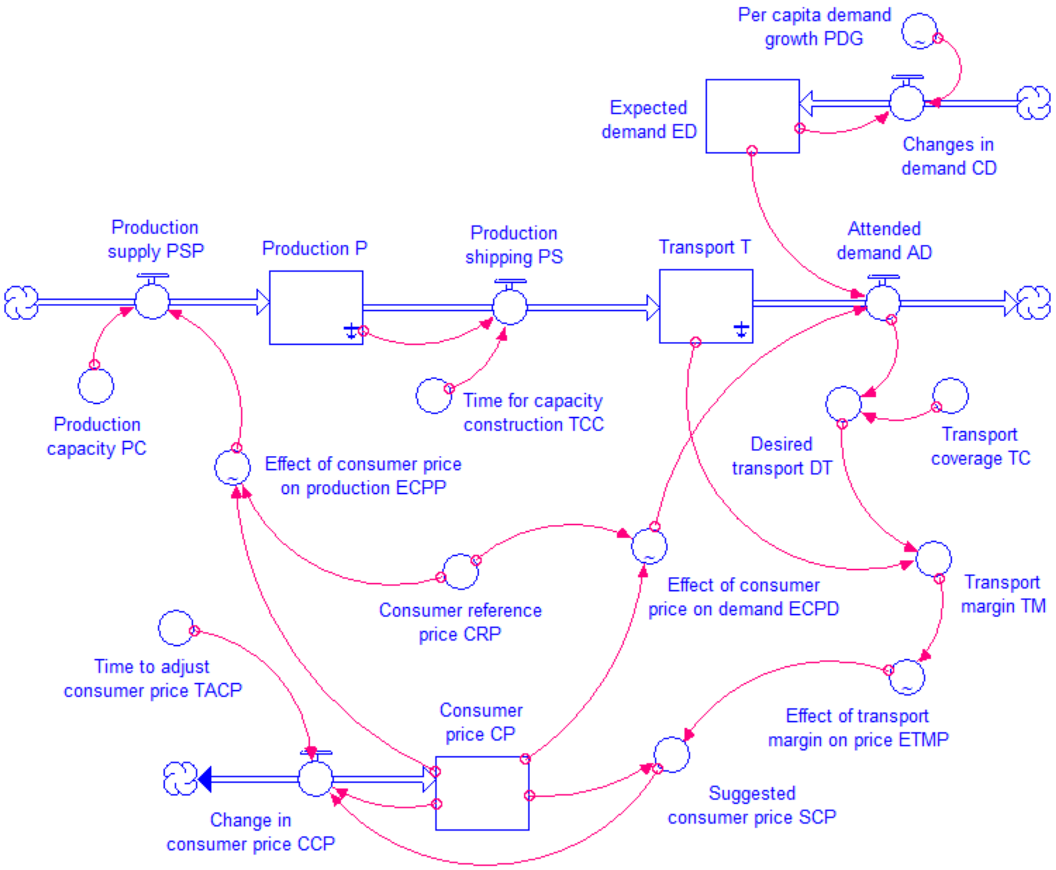


Figure 2. Stock and flow diagram for the natural gas model

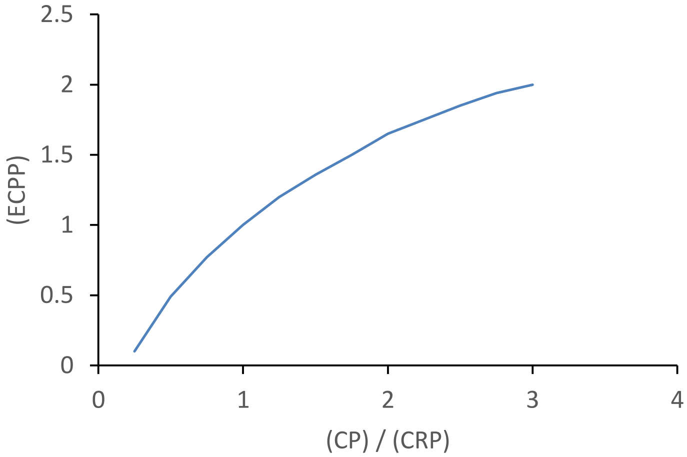


Figure 3. Effect of consumer price on production

The calculation of the effect shown in Figure 3 is based on the relationship between the consumer price (*CP*) with the reference price (*CRP*). This price (*CP*) is the price perceived by the natural gas consumption sectors.

$$\frac{dCP}{dt} = CCP \tag{3}$$

The change in the consumer price (*CPP*) is calculated based on the suggested consumer price (*SCP*), the current consumer price (*CP*) and the time to adjust this price (*TACP*).

$$CPP = \frac{SCP - CP}{TACP} \tag{4}$$

Where the price suggested to the consumer (*SCP*) is calculated based on the price perceived from the consumer (*CP*) and the effect of the transport margin on this suggested price (*ETMP*) as shown in Figure 4.

$$SCP = CP \times ETMP \tag{5}$$

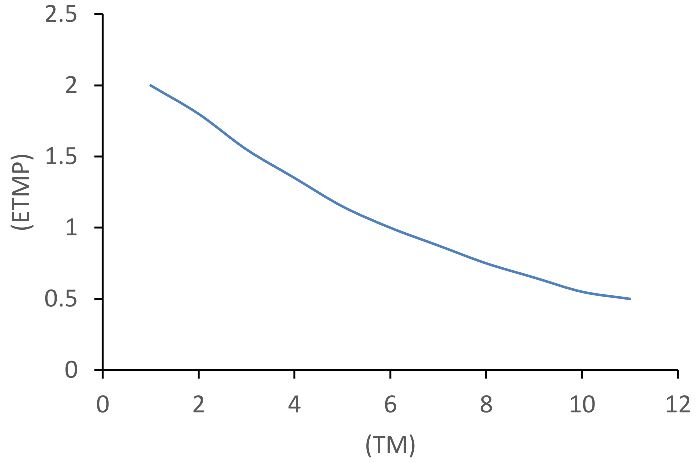


Figure 4. Effect of transport margin on price

The transport margin represents the relationship between the transport levels in the chain (*T*) and the desired transport levels (*DT*).

$$TM = \frac{T}{DT} \tag{6}$$

Where (*DT*) represents the volume of natural gas to be transported in accordance with the demand served (*AD*) and the percentage of coverage (*TC*) to cover this demand while generating supply capacity.

$$DT = AD \times TC \tag{7}$$

The demand served (*AD*) considers the expected demand according to the population growth (*ED*) and effect of the consumer price on this demand (*ECPD*).

$$AD = ED \times ECPD \tag{8}$$

The effect of the consumer price on the demand for natural gas (*ECPD*) is shown in Figure 5.

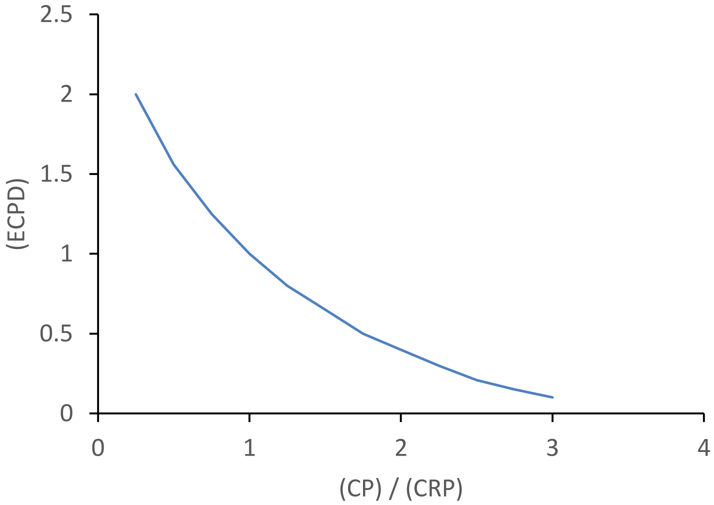


Figure 5. Effect of consumer price on demand

The transport of natural gas (*T*) corresponds to the level of natural gas transported to the final consumer.

$$\frac{dT}{dt} = PS - AD \tag{9}$$

The flow of production deliveries (*PS*) represents the speed with which a given production becomes transport levels to meet the demand, the previous considering a delay for the development of capacity (*TCC*).

$$PS = \frac{P}{TCC} \tag{10}$$

1.2.3 Calibration and validation of the model

For the calibration and validation of the model, we used historical data from the main Colombian public institutions responsible for managing the supply of natural gas, which are UPME (Energy Mining Planning Unit) and Ecopetrol (Colombian Petroleum Company), for the production, transport and demand levels in Giga Cubic Feet (see Figure 6).

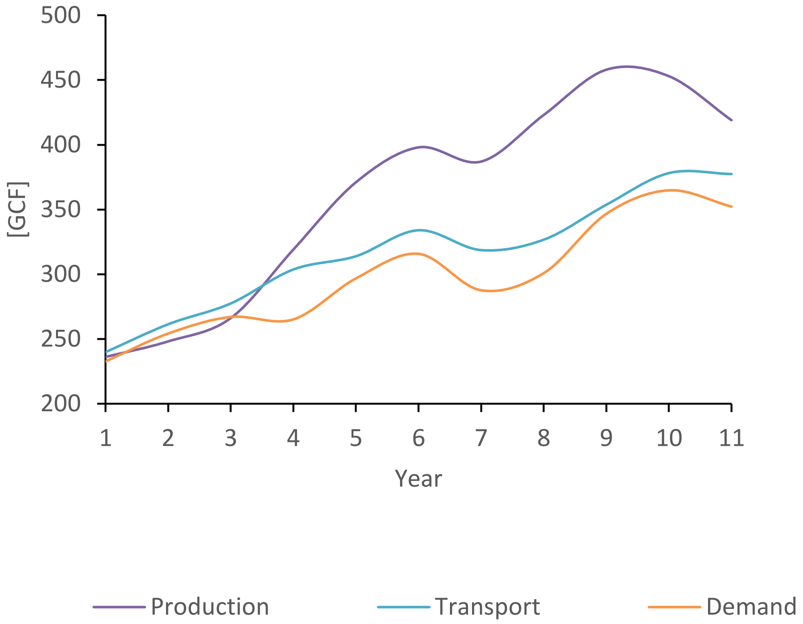


Figure 6. Historical levels of natural gas in Colombia

The calibration consisted mainly of observing the behaviour of production, transport and demand levels. In the case of validation and based on historical information, the values of the parameters included are shown in Table 1. The comparison between these historical data and the simulated values for the production, transport and demand variables are shown in Figure 7.

Parameter	Units	Value
Production initial value (*P*)	CGF	223.36
Production capacity (*PC*)	CGF/Year	163.1
Consumer price initial value (*CP*)	USD	11.12
Consumer reference price (*CRP*)	USD	11.12
Time to adjust consumer price (*TACP*)	Year	1/12
Transport initial value (*T*)	GCF	238.52
Transport coverage (*TC*)	Percentage	6.14%
Time for capacity construction (*TCC*)	Year	2

Table 1. Parameters of the natural gas model

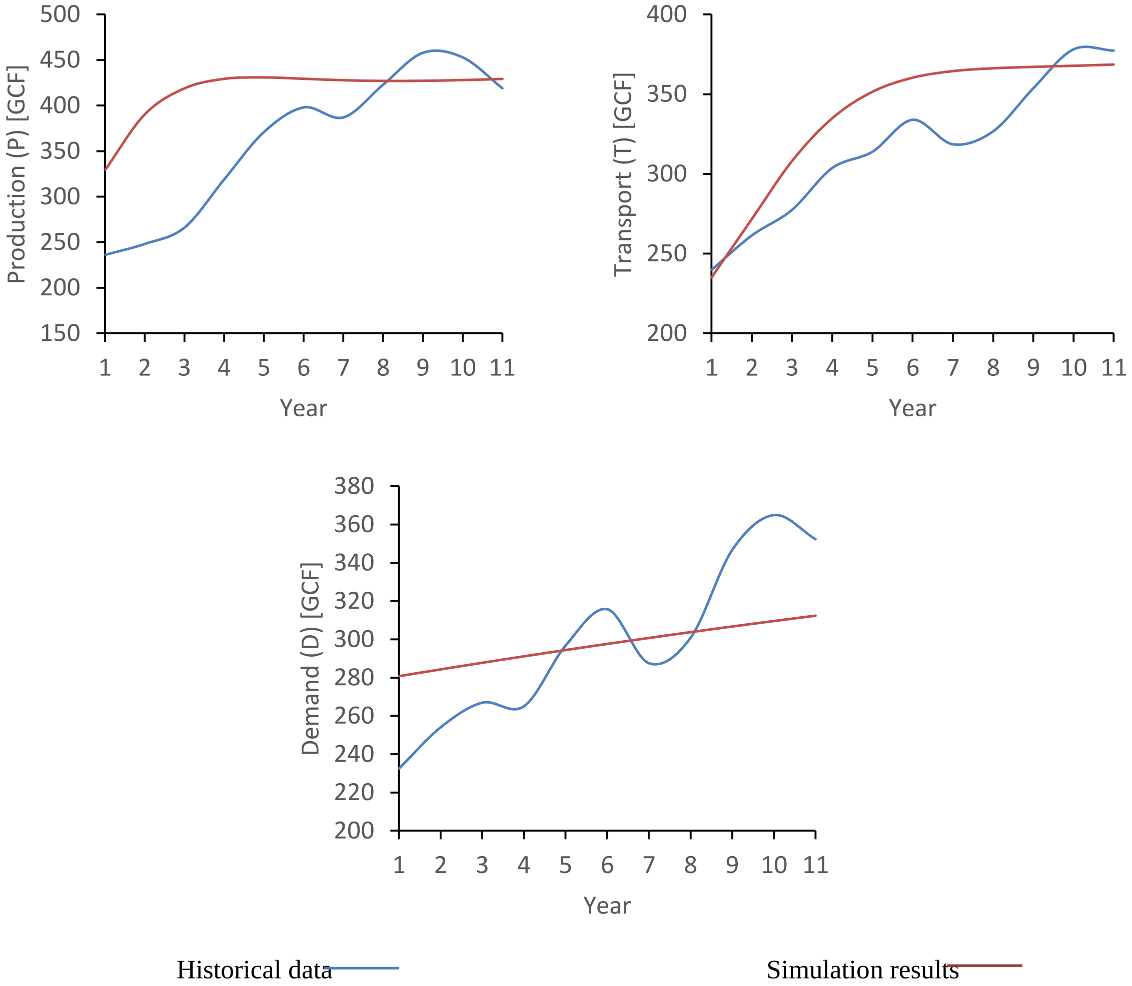


Figure 7. Comparison between historical data and simulation results

In summary, to guarantee the adequate structure or fit of the simulation model, the Mean Squared Error (MSE), the root mean squared error (RMSE), the Mean Absolute Deviation (MAD), and the Mean Absolute Percentage Error (MAPE) were calculated (see Table 2). Based on this, it can be observed that the average MAPE is 12.79%, which shows that the way to represent the variables in the model is adequate.

Variable	MSE	RMSE	MAD	MAPE
Production	6592.7	81.2	63.8	21.76%
Transport	739.0	27.2	23.5	7.48%
Demand	1009.8	31.8	27.0	9.13%

Table 2. Validation of the model (summary)

1.2.4 Scenario analysis in the natural gas model of demand, transport and production

The system dynamics model in this chapter is applied to the Colombian case. A scenario analysis has been carried out to observe the behaviour of the main actors intervening in the supply of this resource for twenty years, changing variables that can be intervened by the decision makers, also by considering resource allocations for the execution of infrastructure projects:

- *Transport coverage (TC):* consists of the percentage of security supply (reserve capacity) that must be considered in order to experience no shortages during the time required for the generation of the new transport capacity. This must respond to the demand of the various mentioned sectors.
- *Time for capacity construction (TCC):* represents the time necessary for the construction of infrastructure projects in transportation, which can be accelerated through higher allocation levels of resources.

The scenarios evaluated in the model are detailed in Table 3 and can be seen in Figure 8.

Variable / Scenario	S1	S2	S3	S4	S5
TC	1.5	3.0	6.1	12.0	24.0
TCC	0.5	1	2	4	6

Table 3. Scenarios for the demand, transport and production model

1.2.1 Results and discussion

The results for the mentioned scenarios are presented and relate to the following variables: production supply (*PSP*), production (*P*), production shipping (*PS*), transport (*T*), attended demand (*AD*) and consumer price (*CP*).

The production supply (*PSP*) is stabilized for all scenarios at 221 [GCF]. There is a delay in this supply given the increase per scenario of the time required for the construction of transport capacity (*TCC*) as shown in Figure 9.

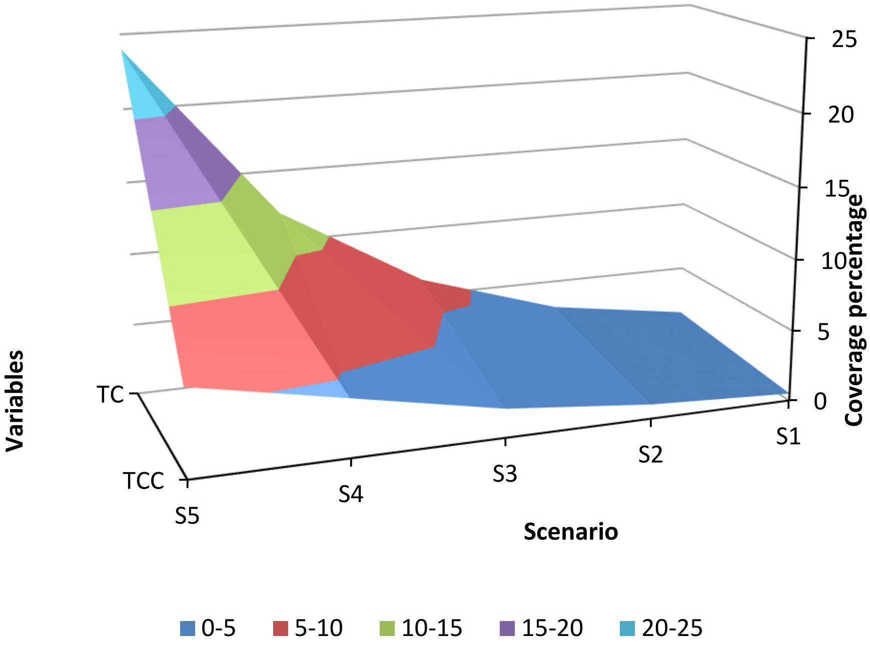


Figure 8. Graphic of scenarios included in the demand, transport and production model

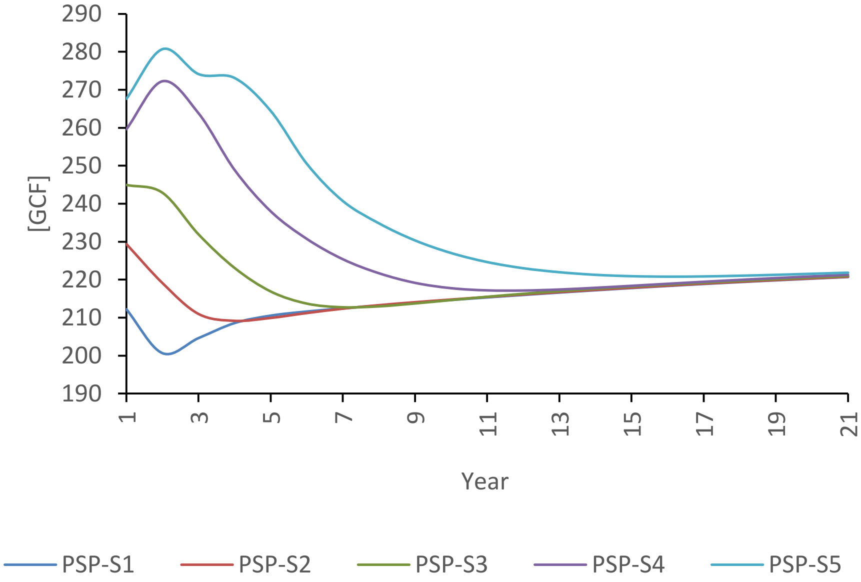


Figure 9. Behaviour of production supply (*PSP*) under five different scenarios

The level of production (*P*) increases by scenario in accordance with the increase of the variables transport coverage (*TC*) and time for capacity construction (*TCC*). For all scenarios, this level converges more quickly if the time for capacity generation is shorter (see Figure 10).

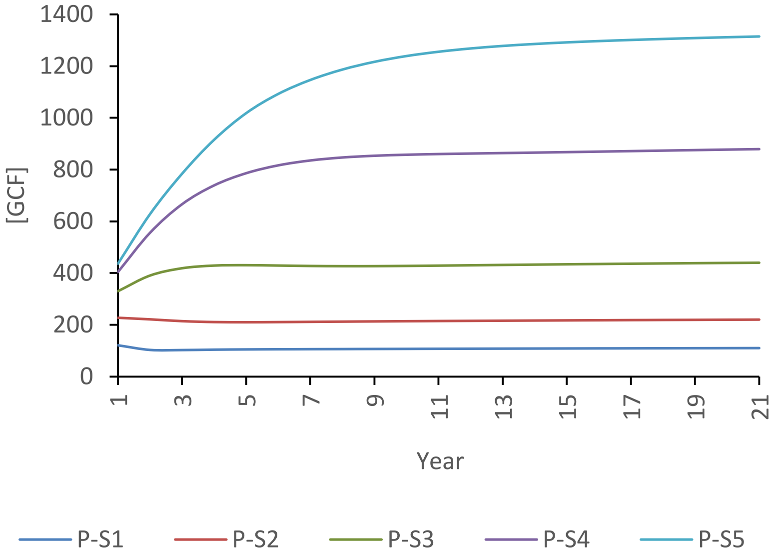


Figure 10. Behaviour of production (*P*) under five different scenarios

The flow of production deliveries (*PS*) is delayed based on the increase in the time required for the construction of transport capacity (*TCC*) and stabilizes from year 13 near 215 [GCF] (see Figure 11).

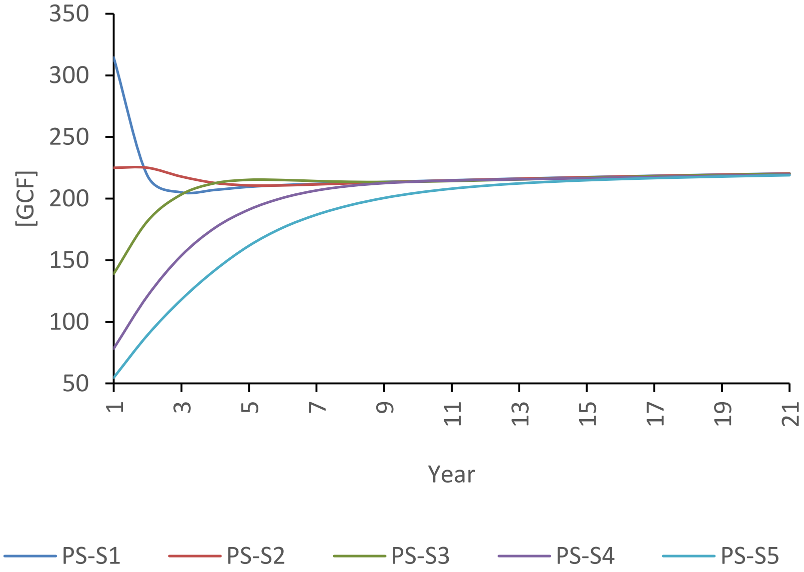


Figure 11. Behaviour of production shipping (*PS*) under five different scenarios

The level of transport responds to the demand for natural gas and presents greater oscillations and delays in the stabilization values when moving from scenario S1 to scenario S5, as shown in Figure 12.

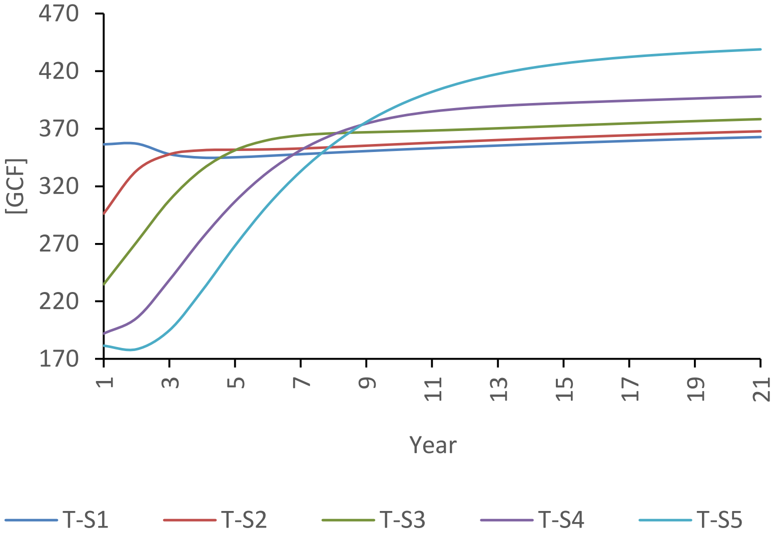


Figure 12. Behaviour of transport (*T*) under five different scenarios

The attended demand (*AD*) exhibits oscillations that correspond to those shown by the previously described variables, stabilizing near the 218 [GCF] as shown in Figure 13.

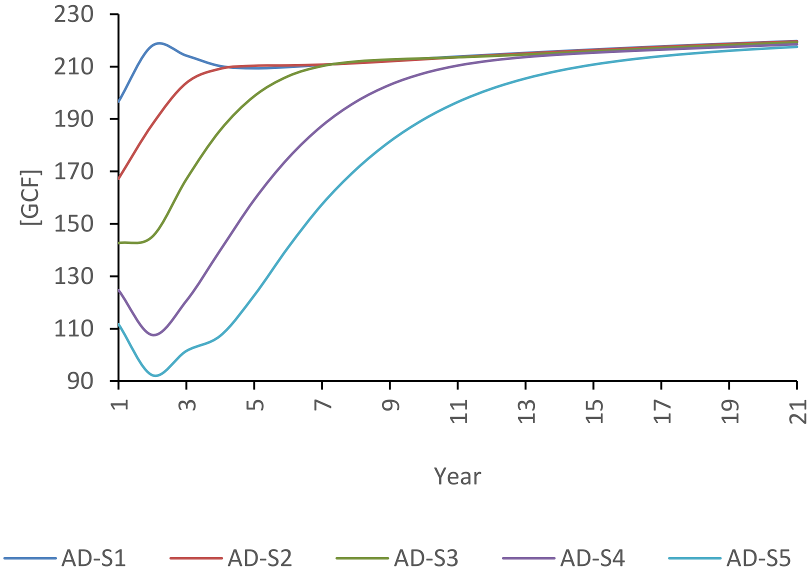


Figure 13. Behaviour of attended demand (*AD*) under five different scenarios

The natural gas demand, transport and production model shows greater fluctuations and values in the consumer price level (*CP*), as the values of the transport coverage (*TC*) and time for capacity construction (*TCC*) increase, according to the scenarios evaluated. This price is stabilized for all scenarios in an approximate value of 16.6 [USD], with an increase in time that responds to the progressive increase in demand for natural gas (see Figure 14).

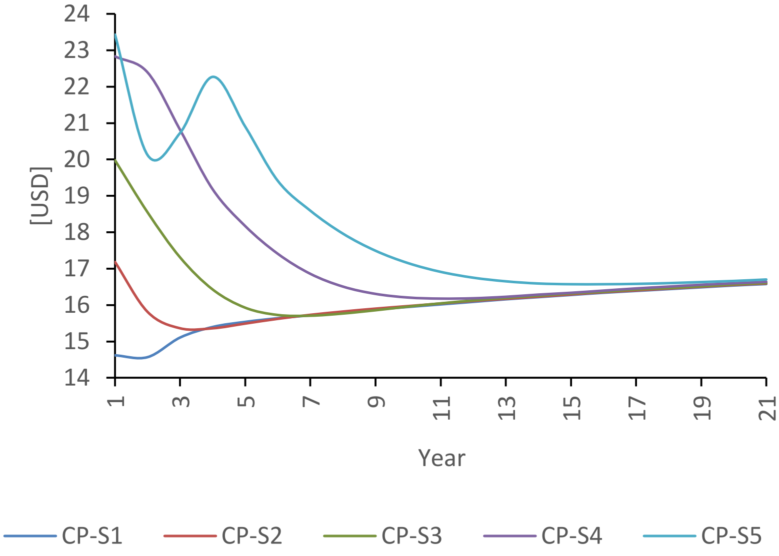


Figure 14. Behaviour of consumer price (*CP*) under five different scenarios

1.3 Concluding remarks

This chapter develops a model that combines the demand, transport and production of natural gas for the Colombian case, through systems dynamics methodology using iThink software, which enables to observe the behaviour of the supply of natural gas in a given time-interval and expected growth in demand.

The reserves of natural gas in some regions of the world have been showing a reduction, while demand has grown in recent years. This situation of imbalance between supply capacity and consumption, makes it important to study public policies that in a coordinated manner, involve various sectors in the effort to meet the requirements of natural gas, as a direct energy source or as a source of energy support for the generation of electrical energy by means of thermoelectric plants.

A thorough review of the literature regarding the modeling of energy supply chains was carried out, highlighting what is related to the supply of natural gas. From this search, it is found that classical research is applied to the planning of the supply of biomass and shale gas, using optimization methods. The structural investigations are oriented to the design, planning and operation of the supply in the case of shale gas, in the case of natural gas, they are oriented to the analysis of the supply networks with the objective of improving the performance in the allocation of resources, using linear programming models.

Recent research is applied to unconventional sources of energy (biomass, biogas, biodiesel and biomethane) and to the reduction of emissions in energy production, in the support to stakeholders in demand planning, investment and location of facilities, through economic models, stochastic programming, mixed-integer programming models (MIP) and Monte Carlo simulation. In the gas sector (liquefied natural gas, shale gas and natural gas), research is highlighted for imports, investment in infrastructure, planning of resources for production, transmission-distribution networks and environmental impact assessment. These investigations use mathematical models, such as, stochastic programming and mixed-integer linear programming, optimization-based model, multi-objective optimization models, supply chain optimization models, optimization programming model, probabilistic models, stochastic de-centralized fractional programming and Dynamic Upstream Gas Model.

The research presented in this chapter seeks to contribute to the study of supply chains using the methodology of systems dynamics, as described above, has not been applied in the study of the reliability and capacity of natural gas supply. At this point, the associated works that were analyzed in this chapter in which system dynamics have been applied are highlighted. These works combine systems dynamics with other modeling approaches (agents based simulation and optimization models), with the objective of allocating resources in the production of natural gas. Others investigate with respect to the production of electrical energy and the projections of the energy market. Additionally, studies develop models to study forecasts (demand behavior and natural gas capacity). In the evaluation of public policies, some works address the supply of electricity, biomethane and natural gas. Some research focuses on the environmental impact of power generation through the reduction of emissions in energy production.

The research work developed in this chapter contributes to the study of energy supply chains, particularly in the supply of natural gas for the production, transport and demand sectors, as well as the analysis of the effects on the mentioned stakeholders, of the implementation delays related with the implementation projects for generation of capacity and levels of reliability (reserves to meet the changes in the demand of the links in the chain). From the state of the art presented, there is no evidence of researches that jointly address the supply chain of natural gas, using the system dynamics methodology and studying the elements of public policy as support to decision makers to guarantee the continuous supply of the resource, which is shown through the model proposed in this chapter.

For the supply-demand analysis of natural gas, five different scenarios are presented in which different times are combined for the construction of transport capacity and percentages of coverage in the transport level, the above, considering the possibility that policy makers allocate resources that speed up the execution times of infrastructure projects and they also select policies in which there are greater or less reserves security in the supply.

Through the scenarios' evaluation, it is possible to observe the effect of delays in capacity generation, by increasing the discrepancy in supply needs between production and transport levels, which respond efficiently to demand requirements. These oscillations increase backwards in the supply chain, in this case between transport and production levels, which is known as the bullwhip effect and has been widely studied from Forrester [65] in supply chain research using systems dynamics.

The increase in the generation times of transport capacity and percentage of coverage presented in the analysis of the scenarios, influences the increase in the price to the consumer and therefore in the increase of the time required to stabilize, which generates a disincentive effect to the demand but a greater interest in the generation of natural gas production.

Chapter 2. Demand and supply model for the natural gas supply chain in Colombia

Charter abstract. Natural gas is considered the transitional fuel for excellence between fossil and renewable sources, considering its low cost, greater efficiency and lesser effects on the environment. This has led to increased demand levels world-wide, requiring the intervention of public and private actors to meet such a demand. In this research, the natural gas supply chain in Colombia is investigated using system dynamics modelling as a tool. The results allow to contrast both the behaviour of the production and transport levels and the behaviour of the demand from the consumption sectors, allowing to identify capacity levels to be developed considering implementation times and percentages of coverage in the supply.

Chapter keywords: Supply Chain, Natural Gas, Systems Dynamics, Modeling.

2.1 Introduction

By 2016, the world consumed around 13276.3 million tons of fuels (primary energy), whose 33.3% corresponds to oil, 28.1% to coal, 24.1% to natural gas, 6.9% to hydroelectric power, 4.5% to nuclear energy and 3.2% to renewable sources. In the same year, 3542.9 million cubic feet of natural gas were consumed worldwide, whose 27.3% was consumed in North America, 4.9% in Central and South America, 29.1% in Europe and Eurasia, 14.5% in the Middle East, 3.9% in Africa and 20.4% in Asia (Pacific). Between 2005 and 2015, consumption increased worldwide by 2.3%. In contrast, the proven reserves of this resource were 6588.8 trillion cubic feet by the end of 2016, whose 6.0% was in North America, 4.1% in Central and South America, 30.4% in Europe and Eurasia, 42.5 % in the Middle East, 7.6% in Africa and 9.4% in Asia (Pacific). Between 2006 and 2016, these reserves grew by 17.9% [66].

In Colombia, natural gas is consumed by two large groups classified into: sectors of generation and non-generation of electricity. Within the non-generation group, there are refineries, petrochemicals, general industry, vehicular consumption and residential consumption. In the period between 1997 and 2014, the total consumption of natural gas in Colombia grew by 74%, going from 567 to 989 MPCD (Million Cubic Feet per Day) within the same period. The non-electric generation group grew by 145%, meanwhile, the electric generation group only grew by 8%. The main increases in consumption are in the vehicular sector with an increase of 1,414% and in the residential sector with an increase of 327%, all in the same period mentioned [64].

System Dynamics modelling has been widely used to address the problem of energy supply. Within the literature review, Cai et al. [67] use a model to provide alternatives in the production of helium. North et al. [44] use an integrated model (system dynamics and agents) for the analysis of energy security, which provides a description of two alternative methods used to study conflicts in energy supply. Bala [53] proposes a model for energy and environment for Bangladesh, in order to generate projections of the supply and demand of energy, evaluating the impact on global warming. Howells et al. [54] use optimization and dynamics modelling including some economic interactions with the energy system, for determining the implementation of measures that impact the emission reduction to the environment. Yücel and Van Daalen [55] use a simulation model based on agents and system dynamics, finding the continuation of the domination of fossil fuels as an energy source, with a change in the use of natural gas to coal using a case base. Eker and Van Daalen [68] study the dynamics of biomethane production in the Netherlands by analyzing the effects of the subsidy policy. Horschig et al. [52] propose a model for the German energy market showing that without incentives plans and financing for R&D programs, the penetration in the country's market of substitutes such natural gas will not be achieved.

As for the main studies related to this research, Bunn et al. [46] develop a model on the electricity market, in which a dominant electricity generator could retail in the electricity and gas markets, due to its size and capacity. Olaya and Dyner [49] use an optimization and systems dynamics model in order to address the sustainability of the natural gas industry, identifying that the integration of modelling methods could be of great value for the formulation, understanding and evaluation of energy policies in the natural gas sector in Colombia. Chyong Chi et al. [69] consider a system dynamics model to investigate the factors that influence the long-term supply and demand of natural gas in the United Kingdom. Jingchun et al. [47] model the trend of supply and demand of natural gas in China under different scenarios between the years 1990 and 2050, allowing them to provide a prediction model of natural gas supply. Li et al. [48] use a model that shows the growth of gas consumption in China between 2010 and 2030. Ponzo et al. [45] develop a model that analyses how regulation influences long-term supply in Argentina and neighboring countries. Eker and Daalen [56] apply a model in which the results show that the objectives in terms of annual production volume, energy consumption and CO_2 emissions can be achieved in the Netherlands only in a small proportion of the future scenarios analyzed. Redondo et al. [70] present a model for the integration of electricity markets in which they study the relationship of supply and demand through the effects of the reserve margin on price and this in turn on capacity building and stimulus to demand.

This chapter is organized as follows: in the modelling section of the supply chain, the hypothesis surrounding this research is presented, based on the analysis of stock and flow structure and causal loop diagrams. Subsequently, the variables and parameters used in the modelling are presented, as well as the verification and validation of the developed model. In the results section, the behaviour related to both production and transport levels to meet the natural gas demand in Colombia are analyzed. Finally, conclusions are presented regarding the main contributions of studying the policies for the supply of natural gas as a dynamic supply chain.

2.2 Natural gas demand and supply model

2.2.1 Causal loop diagram of the natural gas demand and supply model

Taking into account the above literature review, the dynamic hypothesis H_i considered for building the model is based on what was proposed by Whelan et al. [61] in the demand and supply model. This hypothesis can be observed graphically in Figure 15 and is explained below:

- •H_1: by modelling the supply of natural gas in Colombia as a supply chain that integrates its main actors (transport and production), it is possible to observe the levels of capacity required to meet the demand of the national consumption sectors.

Figure 15 shows the main loops included in the model and we explain them below:

- *Transport feedback loop:* the increase in demand for natural gas causes the increase in the need for natural gas to be transported, which considers a percentage of coverage as a safety stock and as a signal for the construction of transport capacity. From the transport level and the aforementioned capacity expansion requirement, the transport margin is calculated, which has an effect on the increase in the suggested price to the consumer, which increases the price perceived by the consumer. This price has an effect on the increase in the generation of transport capacity and therefore in the deliveries of gas produced to be transported. Production deliveries increase the levels of transport capacity under construction, which, considering a delay for their development, increases the levels of natural gas transported.
- *Consumer price feedback loop:* this loop is included in the transport loop, from the transport margin to the price perceived by the consumer. An increase in this price generates a negative effect on the demand and a positive effect on natural gas needed to be transported.
- *Production feedback loop:* the increase in the demand for natural gas to transport, causes the increase in the need for natural gas to be produced, which considers a percentage of coverage as a safety stock and as a signal for building production capacity. Based on the production level and the mentioned capacity expansion requirement, the production margin is calculated, which affects the increase of the suggested price at the wellhead, which, when increased, increases the price received by the wellhead producer. This price influences the increase in the generation of production capacity and therefore in the extraction of natural gas reserves. This increase in reserves, generates an increase in production capacity levels in construction, which considering a delay for its development, increases the levels of natural gas produced.
- *Wellhead price feedback loop:* this loop is included in the production loop, from the production margin to the price received by the producer at the wellhead. An increase in this price generates a negative effect on transport demand, production deliveries and a positive effect on natural gas needed to be produced.

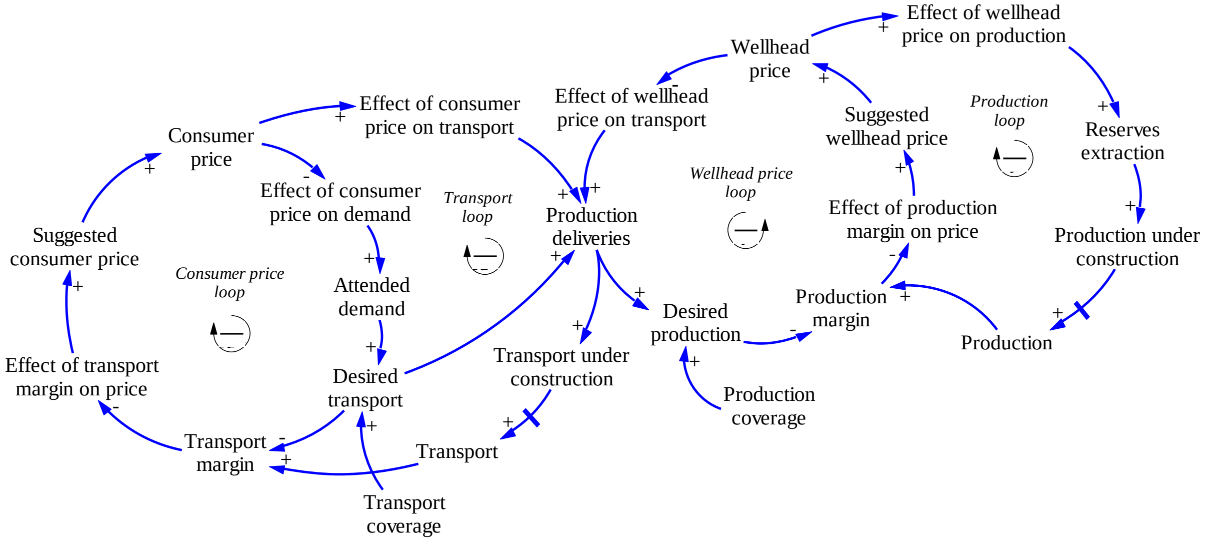


Figure 15. Causal loop diagram of the natural gas demand and supply model

2.2.2 Stock and flow diagram of the natural gas demand and supply model

The stock and flow diagram developed from the causal diagram (see Figure 15) combines the following modelling approaches and can be seen in Figure 16.

- Whelan et al. [61] approach by representing the model of supply and demand as a supply chain for the case of natural gas.
- Cárdenas et al. [62] approach through the generation of capacity to meet the demand for energy in Colombia.

Additionally, the equations of the model developed in the software iThink can be observed in Appendix A.

Within the modelling of demand and supply of natural gas in Colombia, the main actors that intervene in the supply are integrated, as described below [64]:

- *Reserves:* reserves are classified according to the level of certainty associated with the projections and they are also categorized based on the maturity of the project and characterized according to their stage of development and production.
- *Production:* it considers the national production and disposal capacity of natural gas for transportation.

- *Transportation:* it represents the volume of distribution that is related to the National Transportation System (known in Spanish as SNT) and its interconnected networks.
- *Demand:* it includes the industrial, domestic, refineries, compressed natural vehicle gas, petrochemical, electric and residential generation sectors. Considering the estimated population growth in Colombia.

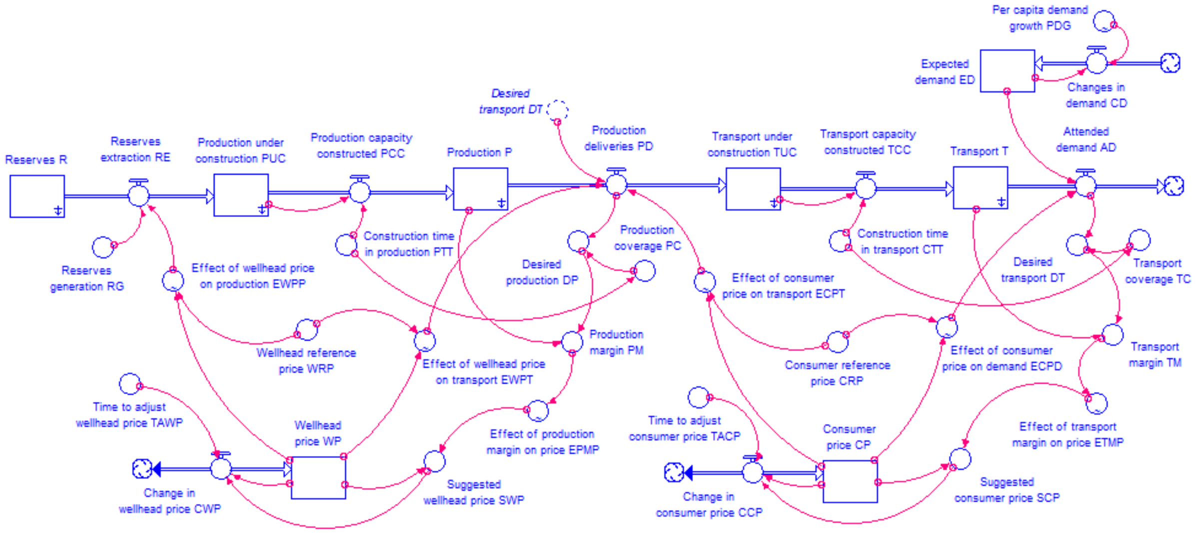


Figure 16. Stock and flow diagram for the natural gas demand and supply model

Within the design of the natural gas supply and demand model, eight stock variables are considered, which represent the changes in the state of natural gas from the generation of reserves to its delivery to the final consumer and in which the demand for the previous actor in the chain, corresponds to the capacity requirements of the subsequent actor. Additionally, variables of this type are considered for consumer and wellhead prices. All this is expressed in Giga Cubic Feet [GCF]. The first level variable corresponds to the production capacity in construction (*PUC*), which represents the capacity needed to be built to meet production demand.

$$\frac{dPUC}{dt} = RE - PCC \qquad (11)$$

Where (*RE*) represents the generation flow of reserves from the speed with which the total reserves of the natural gas are consumed (*R*) and the effect of the price of the wellhead (*EWPP*), as shown in Figure 17a. The calculation of the effects depicted in Figure 17a are based on the relationship between wellhead and consumer prices (*WP* and *CP*) with their respective reference prices (*WPR*) and (*CRP*).

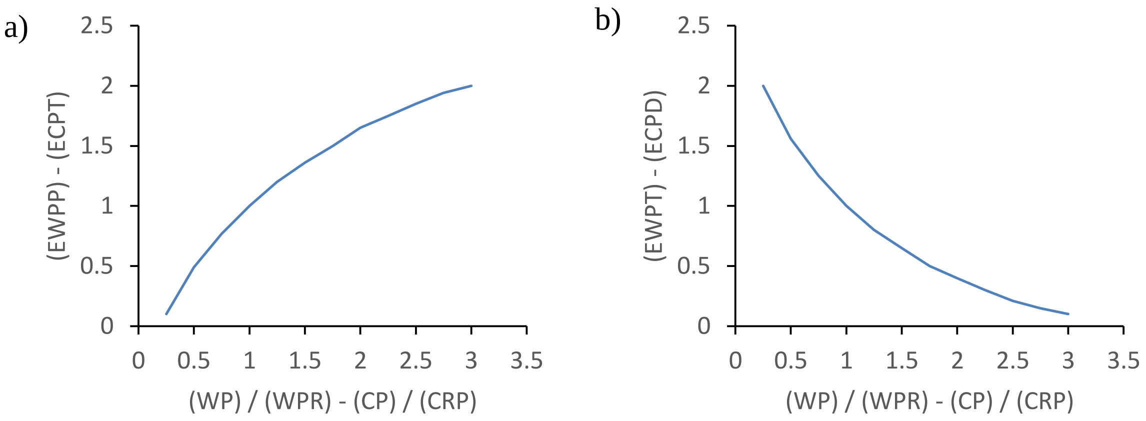


Figure 17. a) Effect of the price at the mouth of the well on the generation of production capacity and effect of the price to the consumer on the generation of transport capacity. b) Effect of the price at the mouth of the well on the generation of transport capacity and effect of the price to the consumer on the demand of natural gas

Production deliveries (*PD*) represent the natural gas produced and available to be transported, which is affected by the desired transport (*DT*), the effect of the consumer price on transport capacity (*ECPT*) and the effect of the price at the wellhead on the generation of transport capacity (*EWPT*). The effect of the price at the wellhead on the generation of transport capacity (*EWPT*) is shown in Figure 17b).

$$PD = DT \times \frac{ECPT + EWPT}{2} \tag{12}$$

The transport capacity under construction (*TUC*) is given by the needs of natural gas to be transported.

$$\frac{dTUC}{dt} = PD - TCC \tag{13}$$

The flow of transport capacity constructed (*TCC*) represents the speed at which the transportation capacity under construction becomes transport levels to meet the demand. Where (*CTT*) represents the time for the construction of transport capacity.

$$TCC = \frac{TUC}{CTT} \tag{14}$$

The transport of natural gas (*T*) corresponds to the level of natural gas transported to the final consumer.

$$\frac{dT}{dt} = TCC - AD \qquad (15)$$

The attended demand (*AD*) considers the expected demand according to the population growth (*ED*), and the effect of the consumer price on this demand (*ECPD*).

$$AD = ED \times ECPD \qquad (16)$$

The wellhead price (*WP*) is the price perceived by natural gas producers.

$$\frac{dWP}{dt} = CWP \qquad (17)$$

The change in wellhead price (*CWP*) is calculated based on the suggested wellhead price (*SWP*), the current price at the wellhead (WP), and the time to adjust this price (TAWP).

$$CWP = \frac{SWP - WP}{TAWP} \qquad (18)$$

Where the suggested price at the wellhead (SWP) is calculated based on the perceived wellhead price (*WP*) and the effect of the production margin on this suggested price (*EPMP*) as shown in Figure 18.

$$SWP = WP \times EPMP \qquad (19)$$

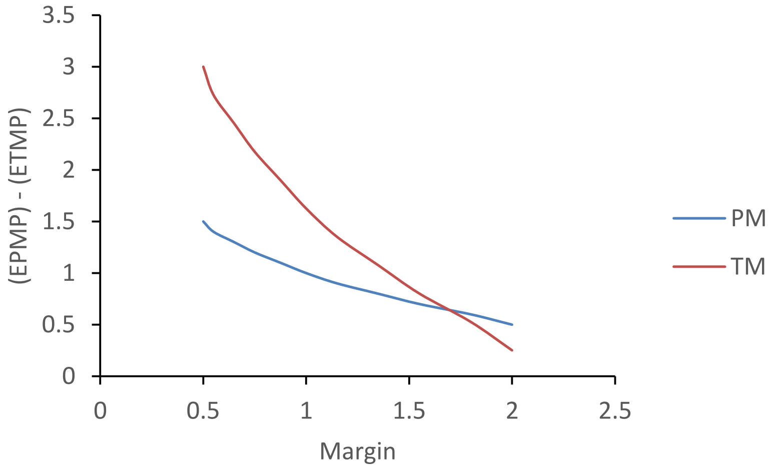


Figure 18. Effect of the production margin on the wellhead price and the transport margin on the consumer price.

The production margin represents the relationship between the production levels in the chain (*P*) and the desired production levels (*DP*).

$$PM = \frac{P}{DP} \tag{20}$$

Where (*DP*) represents the volume of natural gas to be produced according to the production deliveries (*PD*) (transport capacity required) and the percentage of coverage (*PC*) to cover the transport demand while building production capacity.

$$DP = PD \times PC \tag{21}$$

The consumer price (*CP*) is the price perceived by the natural gas consumption sectors.

$$\frac{dCP}{dt} = CCP \tag{22}$$

The change in consumer price (*CPP*) is calculated based on the suggested consumer price (*SCP*), the current consumer price (*CP*) and the time to adjust this price (*TACP*).

$$CPP = \frac{SCP - CP}{TACP} \tag{23}$$

Where the suggested consumer price (*SCP*) is calculated based on the price perceived from the consumer (*CP*) and the effect of the transport margin on this suggested price (*ETMP*) as shown in Figure 18.

$$SCP = CP \times ETMP \tag{24}$$

The transport margin represents the relationship between the transport levels in the chain (*T*) and the desired transport levels (*DT*).

$$TM = \frac{T}{DT} \tag{25}$$

Where (*DT*) represents the volume of natural gas to be transported according to the attended demand (*AD*) and the percentage of transport coverage (*TC*) to cover this demand while transport capacity is being built.

$$DT = AD \times TC \tag{26}$$

2.2.3 Calibration and validation of the model

For the calibration and validation of the model, we used historical data for the levels of reserves, production, transport and demand in Giga Cubic Feet (see Figure 19). The source of this data is the Colombian governmental institution responsible for managing the supply of natural gas, called UPME (Mine Energy Planning Unit), and Ecopetrol (Colombian Petroleum Company).

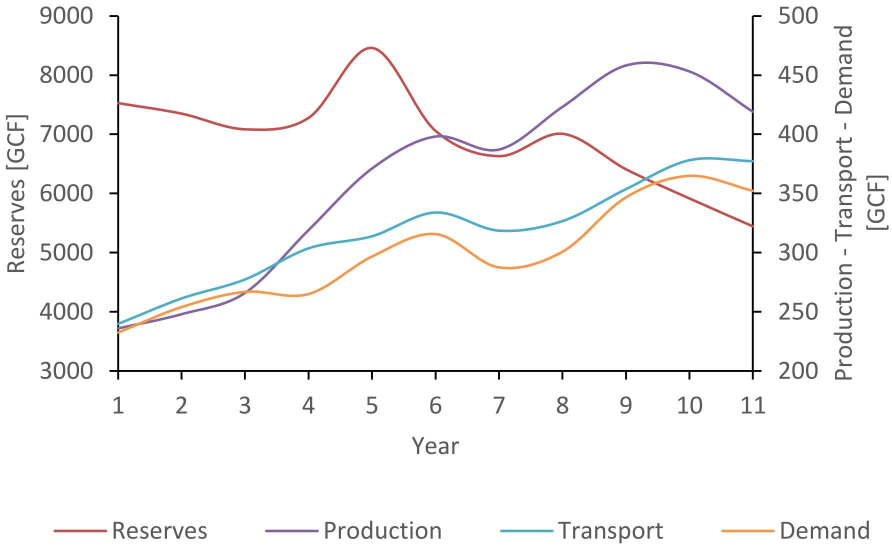


Figure 19. Historical levels of natural gas in Colombia

The calibration consisted mainly of observing the behaviour of the reserves, production, transport and demand levels, each of the actors in the natural gas supply chain. In the case of validation and based on the historical information, the values of the parameters included are shown in Table 4. The comparison between these historical data and the simulated values for the variables of reserves, production, transport and demand, are shown in Figure 20.

Parameter	Units	Value
Initial reserves value (*R*)	GCF	8044.49
Reserves generation (*RG*)	GCF/Year	189.45
Construction time in production capacity (*PTT*)	Year	3
Construction time in transport capacity (*CTT*)	Year	3
Initial production value (*P*)	GCF	223.36

Parameter	Units	Value
Initial transport value (*T*)	GCF	238.52
Time to adjust wellhead price (*TAWP*)	Year	0.25
Time to adjust consumer price (*TACP*)	Year	0.25
Production coverage (*PC*)	Percentage	14.16%
Transportation coverage (*TC*)	Percentage	6.14%
Wellhead reference price (*WRP*)	USD	2.36
Consumer reference price (*CRP*)	USD	11.12

Table 4. Parameters of the natural gas supply and demand model

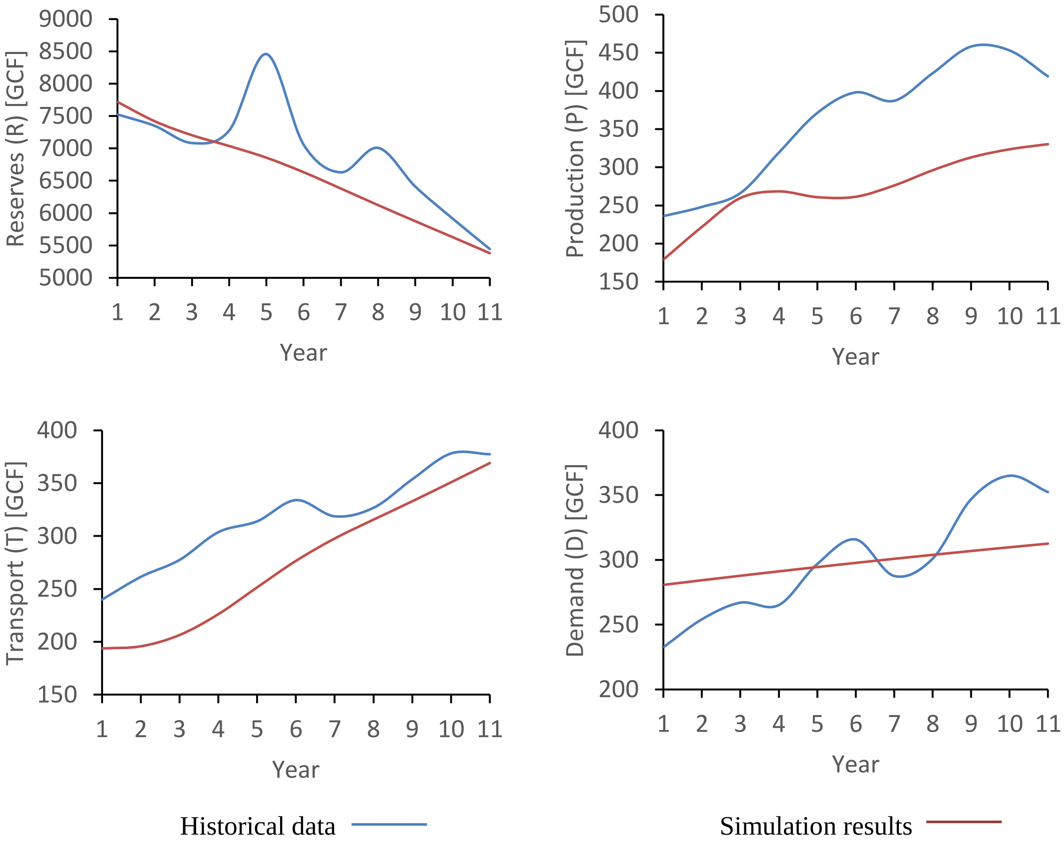


Figure 20. Comparison between historical data and simulation results

2.3 Results and discussion

In the developed model, both the behaviour of production and transport levels are seen as interconnected actors in the natural gas supply chain in Colombia. See results below:

- *Supply and demand in production:* the behaviour of the production variables (*P*), desired production (*DP*), production deliveries (*PD*) and wellhead price (*WP*) are considered.
- *Supply and demand in transport:* the behaviour of the transport variables (*T*), desired transport (*DT*), attended demand (*AD*) and consumer price (*CP*) are considered.

2.3.1 Supply and demand in production

The level of production (*P*) responds to the desired production demand (*DP*) with a delay given by the time of development of production capacity (*PTT*). These two variables seek stabilization near the 400 [GCF]. Production deliveries (*PD*), although showing a similar behaviour, are below with a stabilization value of approximately 285 [GCF]. The wellhead price affects the behaviour of the other variables mentioned in this section. This price is initially close to 5.4 [USD], but in the advance of the simulation it manages to stabilize near the 4.1 [USD], according to the behaviour of supply and demand in production (see Figure 21).

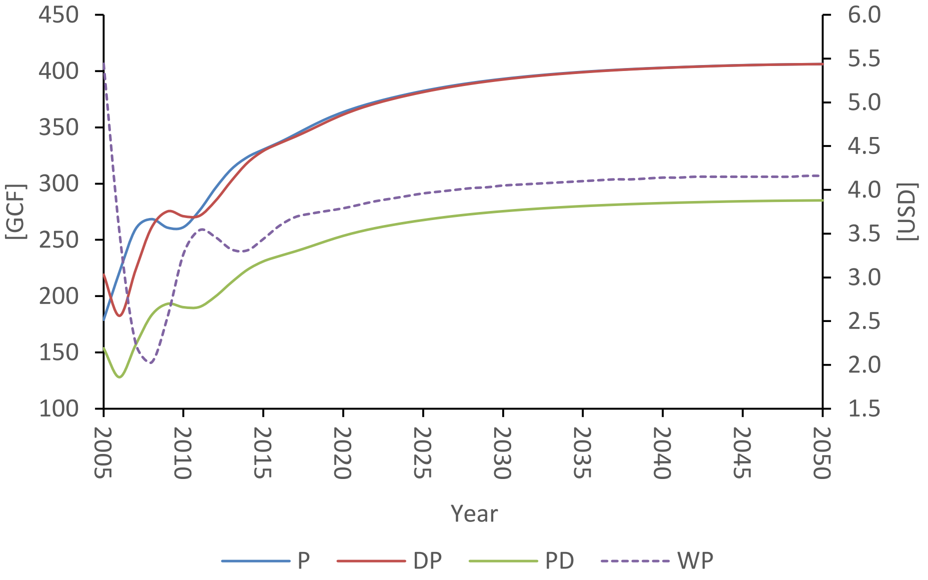


Figure 21. Results of supply and demand in production

Similarly to the next link in the natural gas supply chain in Colombia, the transport level (*T*) shows values greater than the desired transport demand (*DT*), given the interaction with the supply of production and a higher percentage coverage (*TC*). The transport level seeks to stabilize near the 545 [GCF] and the desired transport near the 336 [GCF]. The attended demand (*AD*) is affected by the effect of the consumer price on the demand (*ECPD*) and seeks to stabilize near the 283 [GCF]. The consumer price affects the behaviour of the other variables mentioned in this section. This price is initially close to 23.3 [USD], but in the advance of the simulation it manages to stabilize close to 13.8 [USD], according to the behaviour of supply and demand in transport (see Figure 22).

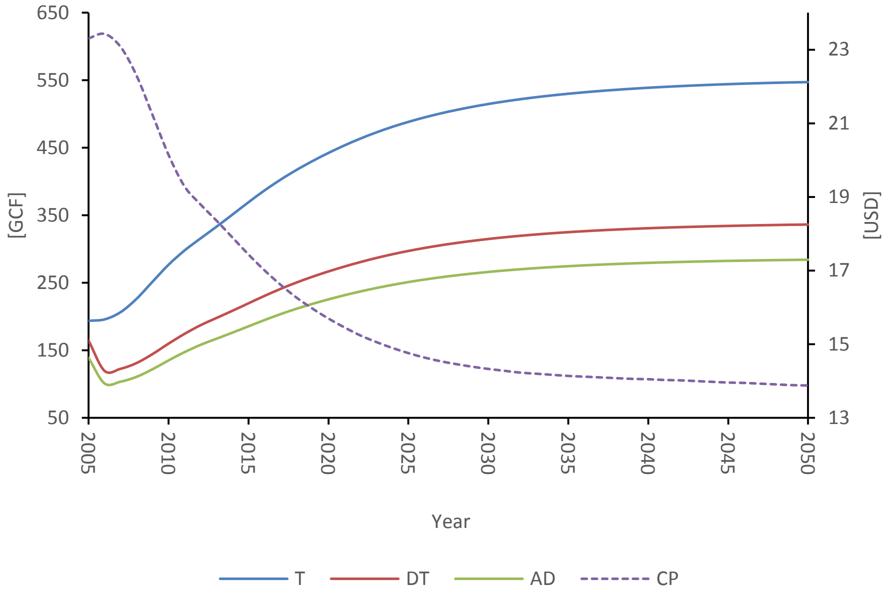


Figure 22. Results of supply and demand in transport

2.4 Concluding remarks

As in some regions and countries of the world, the consumption of natural gas in Colombia has presented a high growth in the last twenty years, on the other hand, the reserves have not increased at the same speed. Situation that is of interest to the national government who is in the obligation to continuously guarantee the supply of the resource, through the integration of both public and private stakeholders, through regulations and incentives for the generation of capacity.

The review of the literature focuses on models that address the methodology of systems dynamics for the study of energy supply. This chapter presents a model that, unlike those of previous research, applies systems dynamics and integrates the actors of the natural gas supply chain, expanding sectors of interest to respond to infrastructure needs that increase capacity of supply, in the production and transport stakeholders, as well as allowing observing the effects of consumer and wellhead prices, as an incentive or not for the implementation of this capacity. The foregoing is highlighted as a novel concept, in terms of the study of the supply of natural gas as an energy supply chain, in which stakeholders are involved from the reserve, production, transport and consumption levels.

In this chapter, the supply of natural gas has been modelled, using system dynamics modelling. This supply chain involves the actors that intervene to meet the demand of the resource coming from various interconnected sectors. This methodology enables to observe the supply-demand relationship among the participant actors, with respect to their related prices (wellhead price and consumer price), through the detailed analysis of the supply capacities (production and transport) under construction and built.

By interconnecting the main actors in the supply chain, it is possible to identify the levels of production and transport capacity that must be generated in the supply of natural gas, which respond to the demand of the various sectors in Colombia. Modelling the supply chain of natural gas, it is possible to observe the behaviour and values of stabilization for the wellhead and consumer prices, as well as the effect of these prices on the levels of production and transport supply, which is very useful for decision makers regarding public policies aimed at affecting the levels of investment to be considered, in the allocation of budgets for the development of infrastructure projects that allow a growth in the levels of reserves, production and transportation of natural gas.

Chapter 3. Supporting the natural gas supply chain public policies through simulation methods: a dynamic performance management approach

Chapter abstract. As mentioned in chapter 2, natural gas is considered the transitional fuel par excellence between fossil and renewable sources, considering its low cost, greater efficiency and lesser impact on the environment. This is the reason why its demand levels have increased worldwide, requiring intervention of public and private stakeholders in order to meet these increments. The participation of diverse interconnected stakeholders (key actors) of the supplier-client form, constitutes a supply chain for natural gas, in which the effects of the application of public policy actions can be analysed over the time, using the Dynamic Performance Management (DPM) approach. The results of the model show the behaviour of the reserves, production and transport levels compared to scenarios that combine the implementation time of capacity expansion projects and supply reliability percentages, where the national government can intervene, facilitating decision makers to identify the impact of the actions to be implemented, as well as in planning policies aimed at guaranteeing the uninterrupted supply of this resource.

Chapter keywords: supply chain, natural gas, energy policies, dynamic performance management, systems dynamics, modelling.

3.1 Introduction

Natural gas is a fossil fuel demanded by different sectors, such as transport, industry, residential, commercial and electric power generation [71]. Its processing requires few stages from the source of extraction until delivery to the final consumer. It is transported safely and efficiently around the world, generating low environmental impact either in the form of liquefied natural gas (LNG) using methane tankers, or through various regions using pipelines. In the generation of conventional energy, natural gas is one of the most efficient fossil fuels compared to other fuels, with a market share of at least 22% of fossil fuels, low costs of power plants, greater flexibility and speed in its construction. When natural gas is used for domestic heating, industrial heating, electricity generation and natural gas vehicles (NGV), produce on average 38% less CO_2 emissions than when using oil, coal, ACPM or gasoline, which contributes to reducing the greenhouse effects, especially in urban areas [6].

Taking into account the low level of proven reserves, the decrease in national production levels, together with the current transport capacity and the increase in natural gas demand, it is considered of great importance to analyze the main actions in public policy, that enable to generate the necessary capacity to guarantee a long-term uninterrupted supply of this energy resource of great importance for diverse public and private sectors. In the analysis of the effect of the application of public policies, it is found that Dynamic Performance Management (DPM) can contribute to the development of this research, given the possibility to involve both the public and the private sector, as well as, to identify the most relevant elements affecting the performance of the analyzed system. Based on the above and considering the characteristics of natural gas supply, the following are the most relevant and related research applying DPM.

DPM is applied in educational institutions. For instance, Cosenz [72] provides tools that allow decision-makers to identify key performance drivers for the achievement of sustainable performance in universities. On the other hand, Bianchi and Salazar [73] research the capacity of the performance measures established by external institutions (government and inspection agencies) with respect to schools. In applying DPM approach for decision-making in public institutions, Bianchi and Tomaselli [74] consider the lack of application of strategic planning in local public policy. Bianchi and Williams [75] show that DPM can strengthen the design of a set of measures aimed at improving results in terms of crime reduction. Another study using DPM as a support to decision making in programs for young people is proposed by Bianchi et al. [76] who analyse how research grounded on a results-based approach, balance different objectives for stakeholders in the policy-making process. Cosenz and Noto [77] explore the causal relationships underlying the impact of corruption on organizational performance.

In the strategic management field, Cosenz [78] [79] studies how system dynamics modeling can be used to support new venture strategy formulation, providing methodological support for the design of Business Models (BM). Regarding its application to small and medium enterprises

(SMEs), Bianchi et al. [80] consider that systems dynamics methodology can add value to their performance management activities. Cosenz and Noto [81] analyze how SMEs are increasingly affected by the aforementioned crisis and the dynamic complexity. Noto G. and Noto L. [82] suggest the application of DPM in the strategic planning processes of the stakeholders in the local public sector. In applying DPM in the supply chain research field, Ren et al. [83] propose an integrated, efficient and effective management system in the supply chains framed as a Dynamic Performance System.

Based on what has been so far discussed, this chapter uses a Dynamic Performance Management approach, aiming to analyse the required capacity of the natural gas supply chain, in response to the demand, as well as to generate discussion regarding the policies that must be implemented to avoid energy shortages. The chapter is structured as follows: in the methodology section the Dynamic Performance Management (DPM) framework is presented. Then, the application of the DPM in the natural gas supply chain for the Colombian case is illustrated based on the use of system dynamics modelling. Finally, the results and conclusions of the model consisting in a set of simulation scenarios are shown and discussed.

3.2 Research Methodology

The supply of natural gas involves public and private stakeholders, so DPM approach can contribute to the dynamic analysis of the interactions of these stakeholders, and to understand how the applied policies can support a better effect on the reliability of the supply. In this section, it is worth noting the connection between the public and private sectors, as well as its contribution in the design of policies using the “instrumental” view of DPM [84], [85].

Figure 23 shows the dynamics that each of the sectors, both public and private, can present. The behavior and performance of both sectors depend on the capacity to generate value and promote sustainable development. The performance of the public sector not only provides feedback through taxes and financial contributions of the community that receive a certain set of services, but also in terms of external contributions, in addition that this feedback is presented in the information flows and in sustainable development policies. In this way, the private sector feedback the public [84].

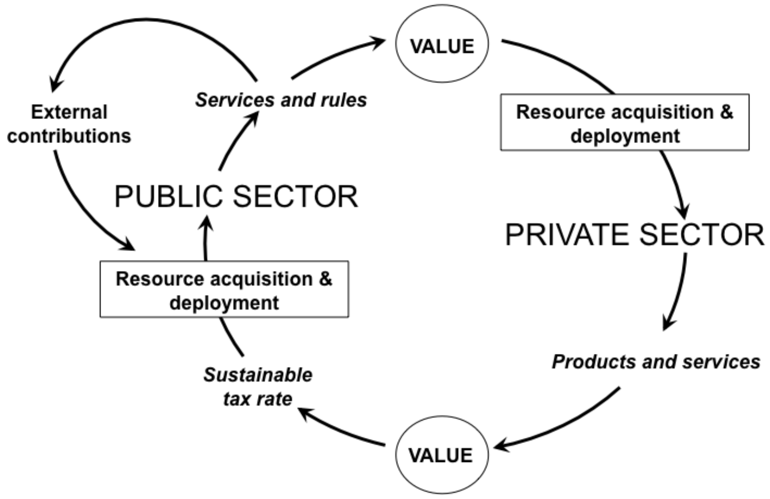


Figure 23. Systematic framework that incorporates the public sector and the private sector

Bianchi [84], [85] once the interactions between the public sector and the private sector have been identified, it is possible to adopt a learning-oriented approach for the development of planning and control systems, which contribute within each responsible area to the improvement of performance in these mentioned sectors. The DPM defines the profiles of each area involved and their relationship with public administration, such as (a) an objective view, (b) an instrumental vision and (c) a subjective point of view (Figure 24).

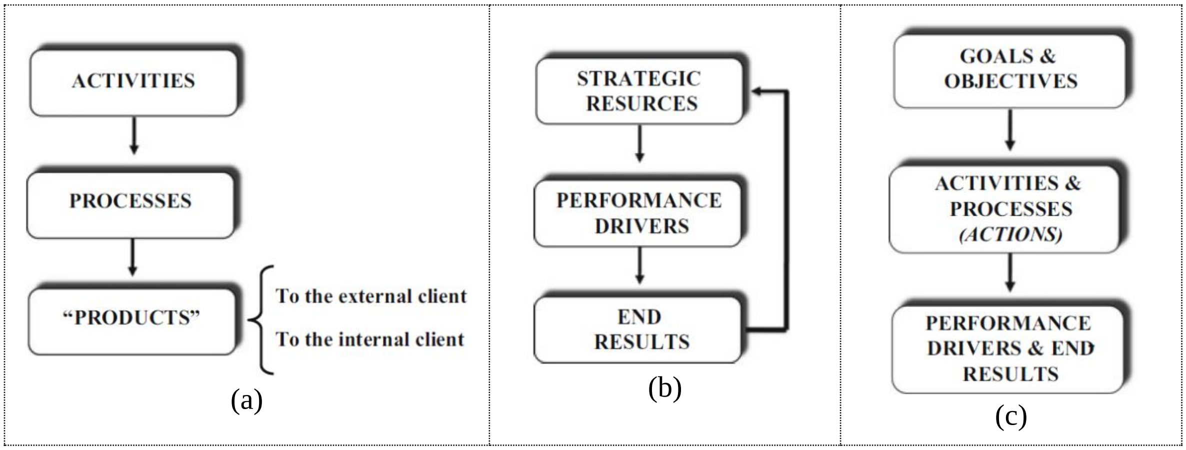


Figure 24. (a) Objective vision, (b) Instrumental vision and (c) subjective point of view

In the objective view it is necessary to define the products generated by administrative tasks (for example, public services). The products are not explicitly the output of a production function, which is transferred to external customers as the end of commercial operations, it refers to the output of administrative tasks with the aim of delivering value to customers, whether external or internal (Figure 24a).

The "instrumental" view defines the means to improve performance, in relation to a specific result associated to the product (or service) provided. In this sense, it is necessary to identify the performance measures related to the end results and the related drivers. To affect these drivers in each of the responsible areas, strategic resources - that are systematically linked to each other - must be built, maintained and deployed (Figure 24b).

The subjective point of view offers a synthesis of the two points of the two previous visions. The pursued results and activities are defined to achieve these objectives that must be included in the plans and budgets of each decision area. This point of view requires performance measurements, that is, an identification of the drivers and the final results, associated with the delivery of the defined products, to later link them with the goals and objectives of the decision makers (Figure 24c).

Using Figure 25, Bianchi [84], [85] represents a synthetic image of the three points of view mentioned above. It shows how in a planning context once defined the products originated by the fulfillment in the administrative tasks, a feedback is required, that is to say, that the processes and related activities are described, to later define the goals and the objectives for each area responsible. These objectives must correspond to the results (and indicators), which will be achieved through actions aimed at managing a strategic resource system. Both drivers of performance and final results should describe whether an organization is able to meet the various expectations demanded by internal and external customers, in terms of the products generated (for example, in terms of volumes, defects, time, cost, etc.).

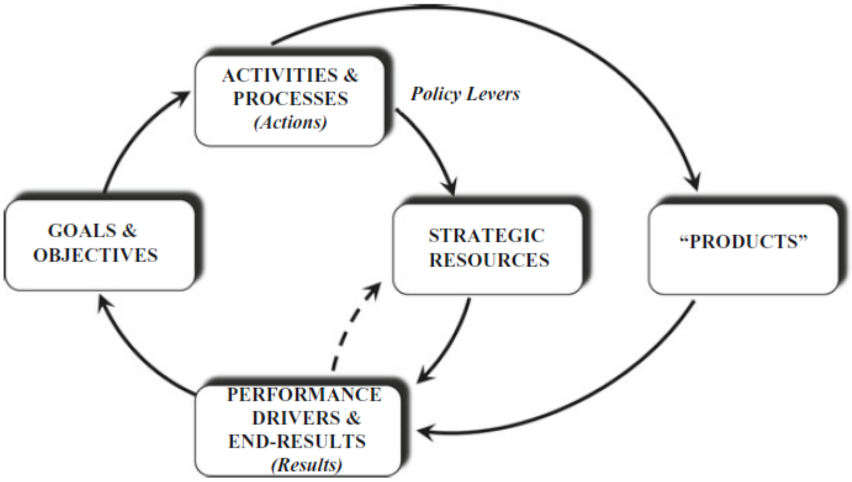


Figure 25. Synthetic framework of the three visions applied to the DPM

As Bianchi [85] maintains, it is important to define the strategic resources, so that they can be modelled as material or immaterial assets available at a given time. Their dynamics depend on the corresponding input and output values that are obtained in the time of the results modelled as in- or out-flows. Such flows are modelled as valves that decision makers can regulate through the incorporated policies, in order to influence the dynamics of each strategic resource and, therefore, through these, in the performance of the organization at both the institutional and inter-institutional level (Figure 26).

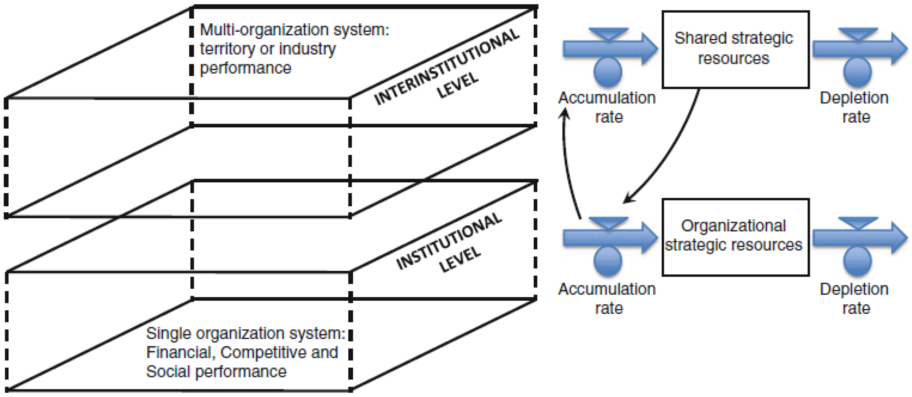


Figure 26. Institutional and inter-institutional levels in the DPM

On the other hand, performance drivers are measures of critical success factors which affect the final performance. These can be measured in relative terms, that is, as a ratio between the actual performance of the organization (perceived by the community or specific groups of users of the services or even competitors) and a benchmark [85]. Finally, the elements considered in the DPM can be analysed by the combination and interaction of the layers (strategic resources, performance drivers, and end results) as shown in Figure 27.

Considering the above, the DPM approach is feasible to be applied both in the public and private sectors, since it allows to develop clear ideas about the performance taking into account the perspective of planning and control, as well as a dynamic approach, contributing in this research by identifying the public policies with the greatest impact on the actors in the supply chain and therefore in the supply of natural gas in the country.

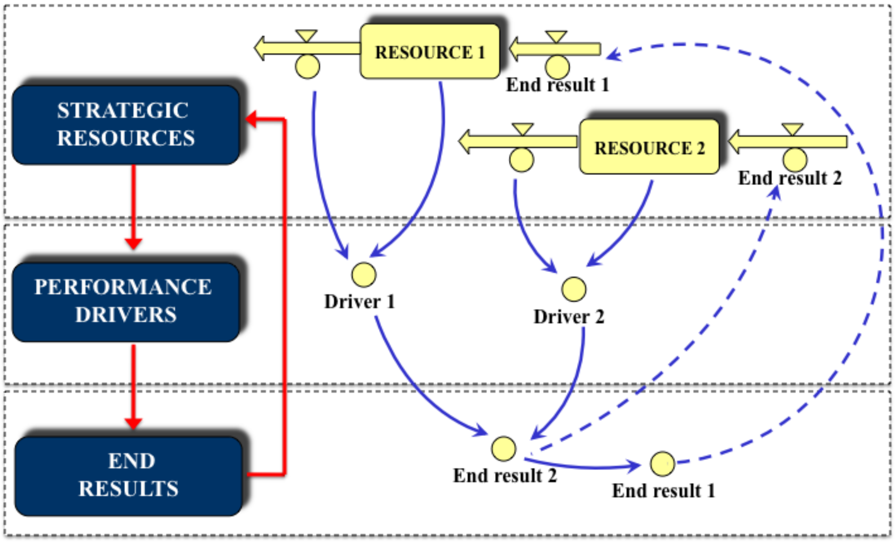


Figure 27. The “instrumental” view of performance management

3.3 Dynamic performance management in the natural gas supply chain

3.3.1 A feedback view of natural gas supply chain

The hypothesis H_i considered for the construction of the model, is based on the proposals by Sterman [63] in modelling supply chains and Eker et al. [56] where the exploitation of natural gas is analysed by means of systems dynamics modelling.

- H_1: the margin of the players in the supply chain of natural gas and the unmet demand of the final consumer are affected by the implementation times of infrastructure projects and defined reliability percentages, guaranteeing the uninterrupted supply of the resource.

Figure 28 displays the main loops included in the model and we explain them below:

- *Transport supply*: the increase in demand for natural gas by the final consumption sectors (industrial, domestic, refineries, compressed vehicular natural gas, petrochemical, electric and residential), causes an increase in the need for natural gas to be transported, which after adjusting the current transport capacity with respect to the expected coverage to avoid shortages, generates the need for transport capacity and considering a delay for its construction.
- *Production supply*: the increase in the requirement of natural gas to transport, causes an increase in the need for natural gas to produce, which after the adjustment of the current

production capacity with respect to the expected coverage to avoid shortage, generates the need for capacity of production and considering a delay for its construction.

- *Reserves supply*: the increase in the requirement of natural gas production, causes an increase in the need to develop natural gas reserves, which after the adjustment of the current generation capacity of reserves with respect to the expected coverage to avoid shortages, generates the need of capacity in the generation of these reserves and considering a delay for their development.

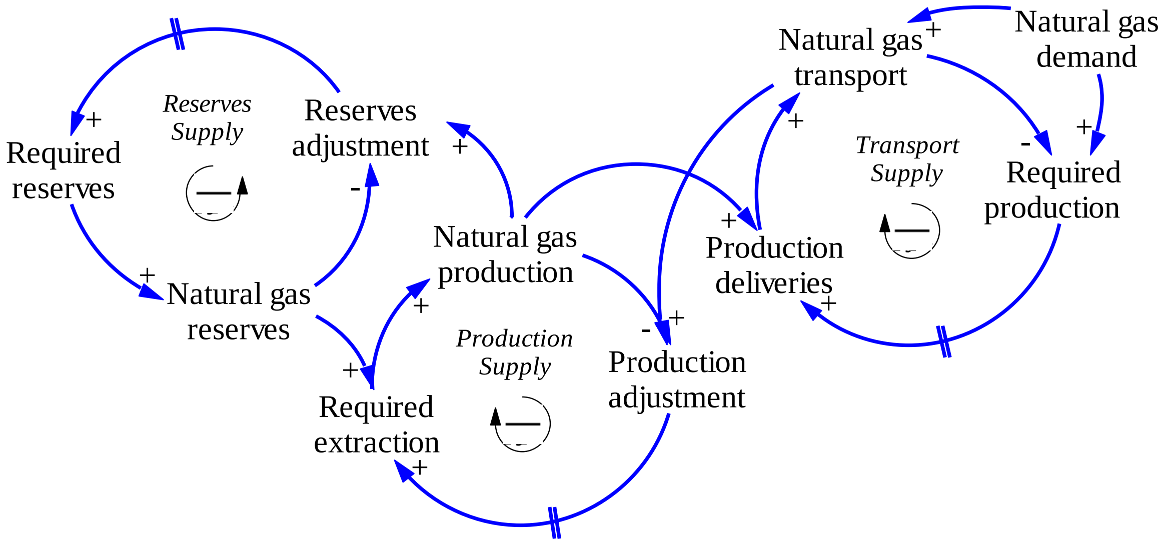


Figure 28. Causal loop diagram for the natural gas supply model

3.3.2 Stock and flow diagram of the natural gas supply chain

The stock and flow diagram developed from the causal loop diagram (Figure 28), combines the following modelling approaches and can be seen in Figure 29. Additionally, the equations of the model developed in the software iThink can be observed in Appendix A.

- Sterman's approach [63] through the inventories replacement by adjusting the demanded requirements, comparing the current levels with the minimum levels of security to be maintained (supply reliability), which avoid the shortage in the supply of the products that flow into the chain considering the lead time of the supplier as a delay in the generation of capacity.

- Eker’s approach [56] which presents the upstream exploitation as the life cycle of a natural gas field, analysing its states from the prospected resources, going through the development of reserves until the production stage.

Within the modelling of the supply chain of natural gas in Colombia, the main stakeholders that intervene in the supply are integrated [64].

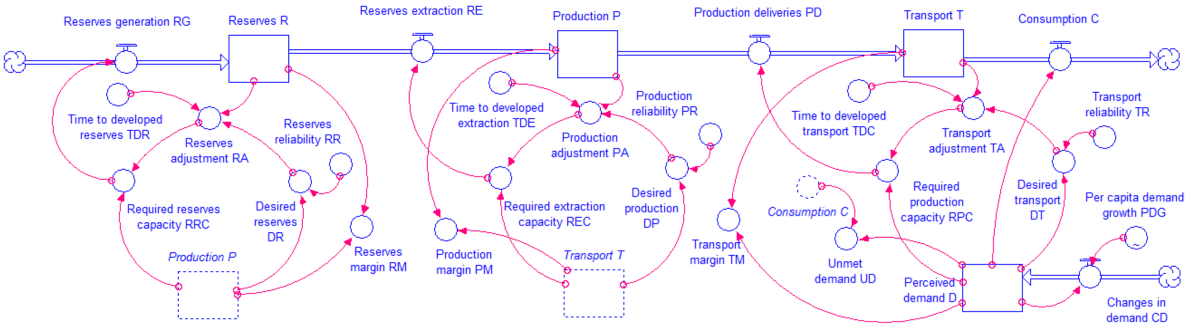


Figure 29. Stock and flow diagram for the natural gas supply chain model

Within the design of the supply chain model, four interconnected stock variables are considered, which represent changes in the state of natural gas, from the generation of reserves to delivery to the final consumer. The demand for the previous link (player) in the chain, corresponds to the requirements of the following link, all this expressed in Giga Cubic Pipes [GCF]. The first stock corresponds to the reserves of natural gas (R), which represents the stocks of proved, probable and possible reserves, given by:

$$\frac{dR}{dt} = RG - RE \tag{27}$$

Where (RG) represents the generation flow of reserves, from the required capacity of these reserves (RRC):

$$RG = RRC \tag{28}$$

The reserve extraction (RE) flow is given by the required extraction capacity (REC):

$$RE = REC \tag{29}$$

The next stock in the chain is represented by the production of natural gas (*P*), the result of the treatment that the plants make to the natural gas extracted so that it can be transported to the final consumer, this is defined as follows:

$$\frac{dP}{dt} = RE - PD \qquad (30)$$

Where (*PD*) represents the flow of production deliveries, which is given by the required production capacity (*RPC*):

$$PD = RPC \qquad (31)$$

The next stock considered in the supply chain, corresponds to the transportation of natural gas (*T*) to the different consumption sectors, and is calculated by means of the following equation:

$$\frac{dT}{dt} = PD - C \qquad (32)$$

Where (*C*) represents the consumption of natural gas in the country, which is equal to the total demand of the consumer sectors. The natural gas demand level (*D*) represents the national consumption of the resource and is calculated as follows:

$$\frac{dD}{dt} = CD \qquad (33)$$

Where (*CD*) represents the changes in demand, which are given by the initial level of demand and the estimated per capita growth based on the population growth (*PDG*):

$$CD = D \times PDG \qquad (34)$$

The required capacities in the natural gas supply chain is represented in a general form by the variable (*Ci*), which affects the inflows of the stocks (reserves, production and transport), are calculated by means of the following equations:

$$C_i = D_{i+1} + Ad_i \qquad (35)$$

$$Ad_i = \frac{Dvd_{i+1} - Lv_i}{Dl_i} \qquad (36)$$

$$Dvd_{i+1} = D_{i+1} \times (1 + Cp_i) \qquad (37)$$

Where:

- i: sub-index indicating the key actors in the supply chain model (1 = reserve level, 2 = production level, 3 = transport level).
- D_{i+1}: demand level of the next key actor ($i + 1$).
- Ad_i: adjusted value of supply requirements of key actor i.
- Dl_i: time to make the adjustment to the demand in key actor i, given the delay in the generation of capacity.
- Lv_i: current level of key actor i.
- Dvd_{i+1}: desired values of demand by the next key actor (i + 1).
- CP_i: coverage percentage (reliability) of the key actor i.

The supply margins are presented as the supply and demand relationship, and are a performance indicator of the existing balance between the ability of the system to respond to the requirements of each link in the supply chain [86]. Therefore, the margins are calculated for the three stakeholders: transport (transport margin TM), production (production margin PM) and reserves (reserves margin RM).

$$TM = \frac{T}{D} \tag{38}$$

$$PM = \frac{P}{T} \tag{39}$$

$$RM = \frac{R}{P} \tag{40}$$

The main goal of the natural gas supply chain is to guarantee the uninterrupted supply of this resource, so that as a measure of performance in its management, unmet demand (UD) is calculated:

$$UD = D - C \tag{41}$$

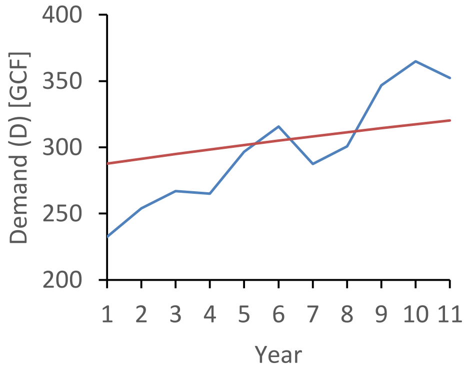
3.3.3 Model calibration and validation

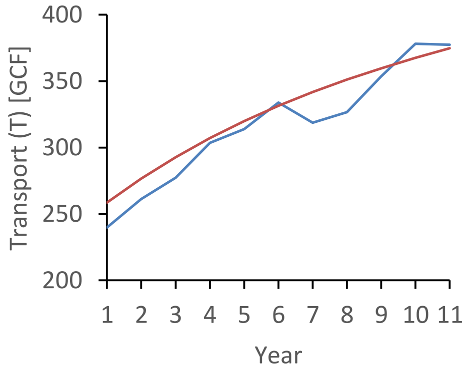
For the calibration and validation of the model, historical data for the stocks of reserves, production, transport and demand in Giga Cubic Feet are used. Data are obtained from the main Colombian national institutions responsible for managing the supply of natural gas, called

UPME (Mine Energy Planning Unit) and Ecopetrol (Colombian Petroleum Company). The calibration process consisted mainly of observing the behaviour of the stocks reserve, production, transport and demand, each one as a link in the natural gas supply chain. In the case of validation and based on the historical information, the values of the included parameters are shown in Table 5. The comparison made between these historical data and the simulated values for these variables are shown in Figure 30.

Supply chain link	Parameter	Measure unit	Value
Reserves	Reserves initial value	GCF	8044,491
	Time to developed reserves (*TDR*)	Year	20
	Reserves reliability (*RR*)	Dimensionless	0,15
Production	Production initial value	GCF	223,36
	Time to developed extraction (*TDE*)	Year	6
	Production reliability (*PR*)	Dimensionless	0,4
Transport	Transport initial value	GCF	238,52
	Time to developed transport (*TDC*)	Year	6
	Transport reliability (*TR*)	Dimensionless	0,3

Table 5. Data of the parameters used in calibration and validation





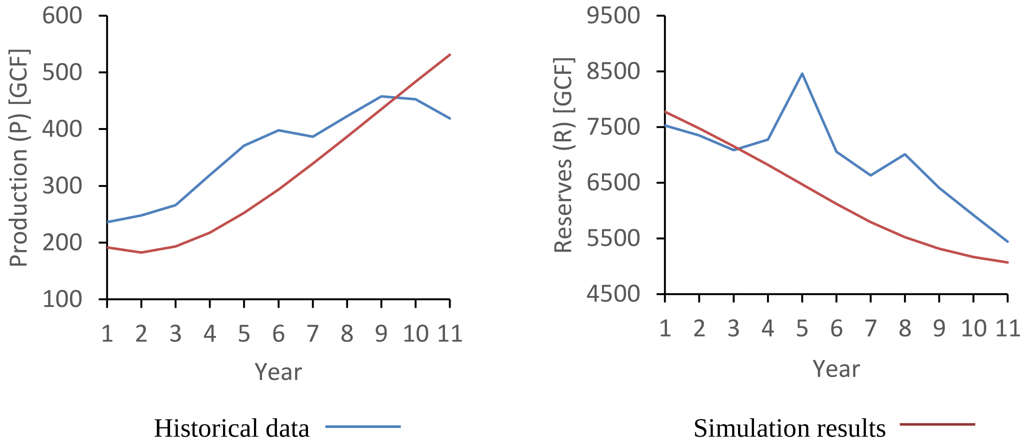


Figure 30. Comparison between historical data and simulation results

3.3.4 Dynamic Performance Management approach for the natural gas supply chain

Dynamic Performance Management (DPM) approach has been used in this chapter with the aim to analyse the effect of government interventions to guarantee the natural gas supply in the country, through the allocation of resources that, on the one hand, foster the acceleration in the implementation of infrastructure projects that increase the capacity of the stakeholders in the chain (required time for capacity development, *TDR*, *TDE* and *TDC*) and, on the other hand, increase the levels of reliability in the supply of the resource (*RR*, *PR* and *TR*). From this, the policy levers are defined for each link in the chain, in terms of reliability (percentage of security) and time for capacity development (required years for implementation).

Figure 31 shows the effect of the policy levers (diamond shapes) on the performance drivers (required capacities), which respond to the demanded levels in the client-supplier relationship, that is, the supplier responds to the supply requirements of the next key actor in the chain (customer), with the main purpose of guaranteeing the attention of the final consumer's demand (perceived demand), by advancing and transforming natural gas trough reserve levels, production and transportation of the supply chain (strategic resources).

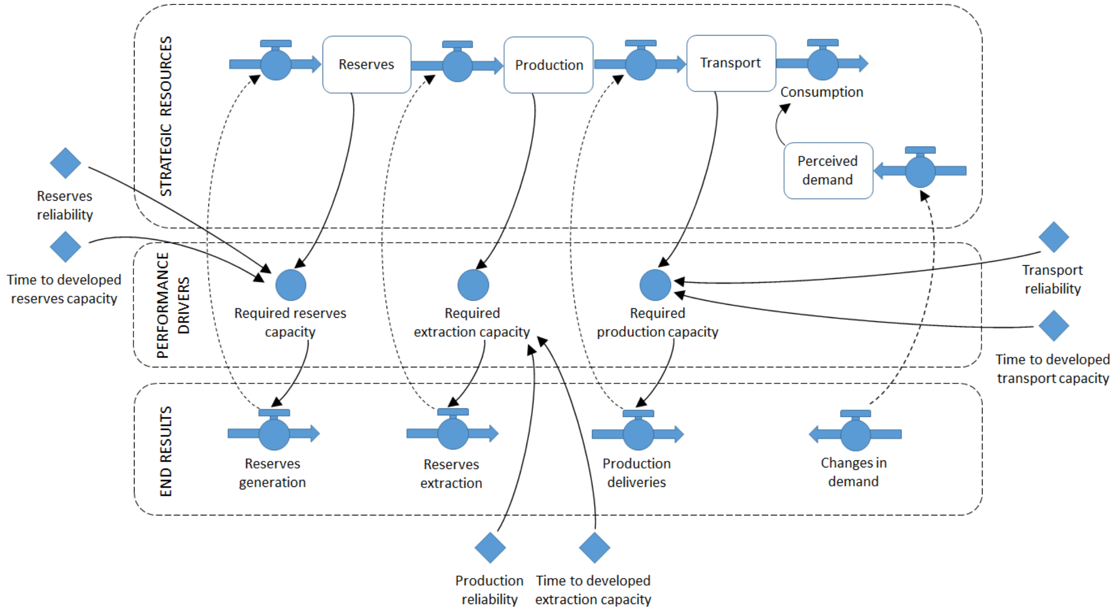


Figure 31. The "instrumental" view of performance management for the natural gas supply chain in Colombia

3.3.5 Scenarios analysis in the natural gas supply in Colombia

As previously mentioned, Colombia is taken as a case study for modelling the natural gas supply chain. Through the analysis of scenarios, it is possible to observe the behaviour of the stock through the instrumental view of the DPM, as function of changes in the policy levers defined until the year 2050 (see Figure 31). These changes are presented in three scenarios S1, S2, and S3 for the policy levers related to the development time of supply capacity in the chain stakeholders (*TDR*, *TDE*, and *TDC*) and for the policy levers related to the percentages of reliability or safety (*RR*, *PR* and *TR*). The proposed changes to these policy levers can be seen in Figure 32.

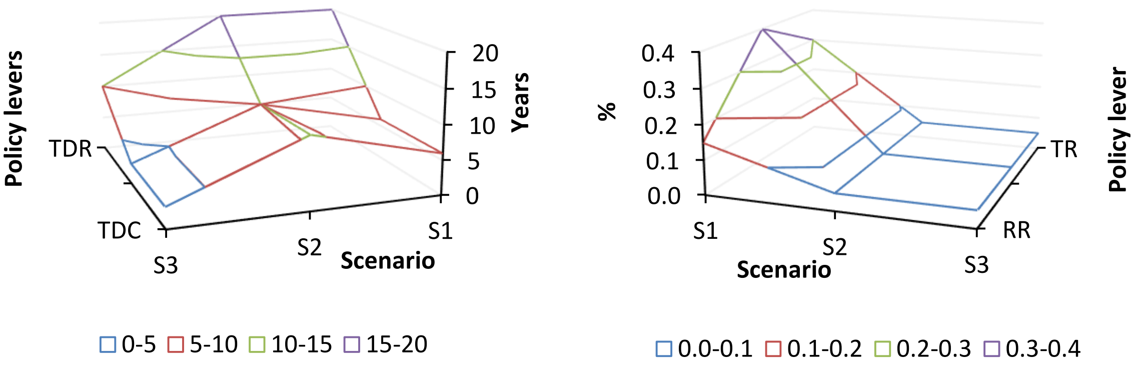


Figure 32. Policy levers changes per scenarios for the natural gas supply chain model

The results for the strategic resources show a stable demand for all the scenarios (considering that the objective of the supply chain is the uninterrupted supply). Natural gas levels show higher values in scenario S1, which is derived from higher reliability percentages. Scenario S2 shows shortages starting in 2032, due to the increase in response times in capacity development. By means of scenario S3, it is possible to meet demand with minors in strategic resources, maintaining low levels of reliability percentages and reducing capacity generation times (see Figure 33).

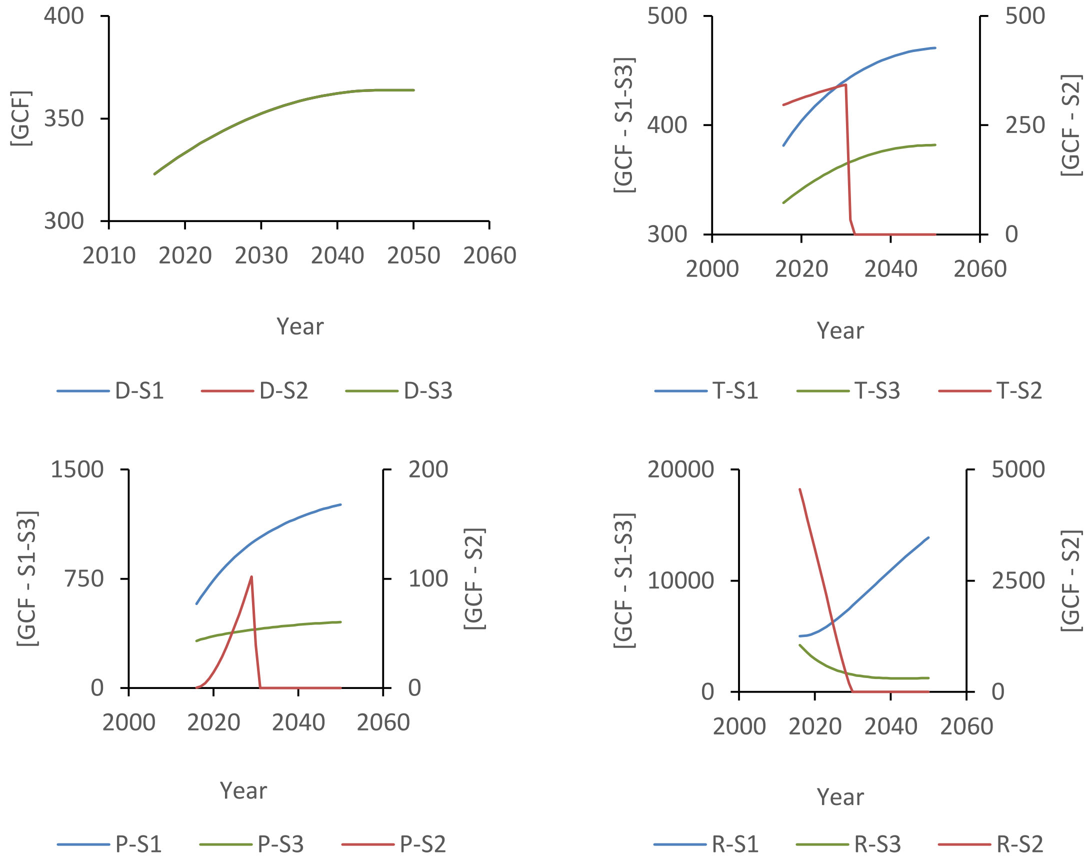


Figure 33. Behavior of strategic resources in the natural gas supply chain model under three different scenarios

Performance drivers respond to the required supply levels based on the reliability percentages in scenarios S1 and S3, with lower values in scenario S3, given that capacity generation times are lower compared to the other scenarios. In scenario S2 the performance drivers of the *RRC* and *REC* respond to the shortage of the chain, on the other hand, the *RPC* performance driver given the raising the capacity requirements for the transport key actor, seeks to respond to the demand needs of the final consumers *D* (see Figure 34).

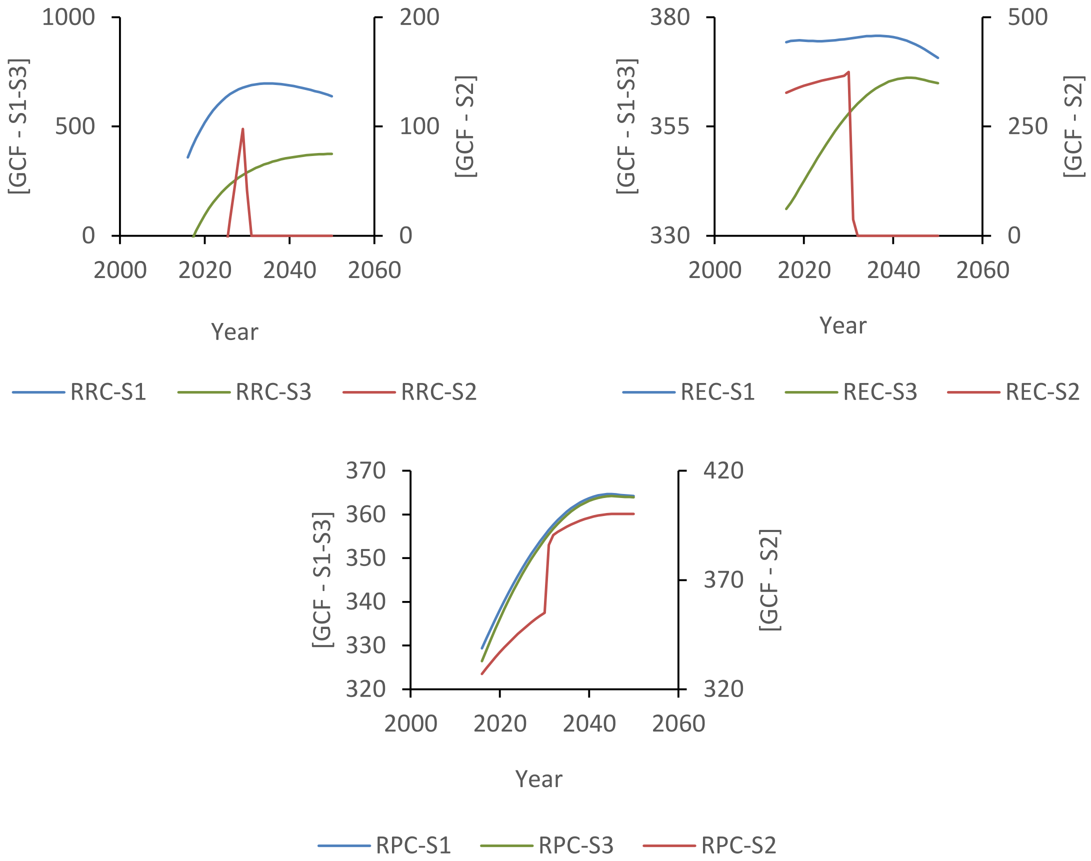


Figure 34. Behavior of performance drivers in the natural gas supply chain model under three different scenarios

In the final results for scenarios S1 and S3, if the supply chain is observed backwards, that is, from the client to the suppliers, there is an increase in the discrepancy of transport, production and reserving stocks, effect widely studied in the supply chain models employing system dynamics, which is known as the bullwhip effect [65]. Scenario S1 shows a peak in the increase in the case of reserves *R*, given that initially reserves are not generated by the volume in which they are counted, but subsequently they fall by the configuration of the policy levers established for this scenario (see Figure 35).

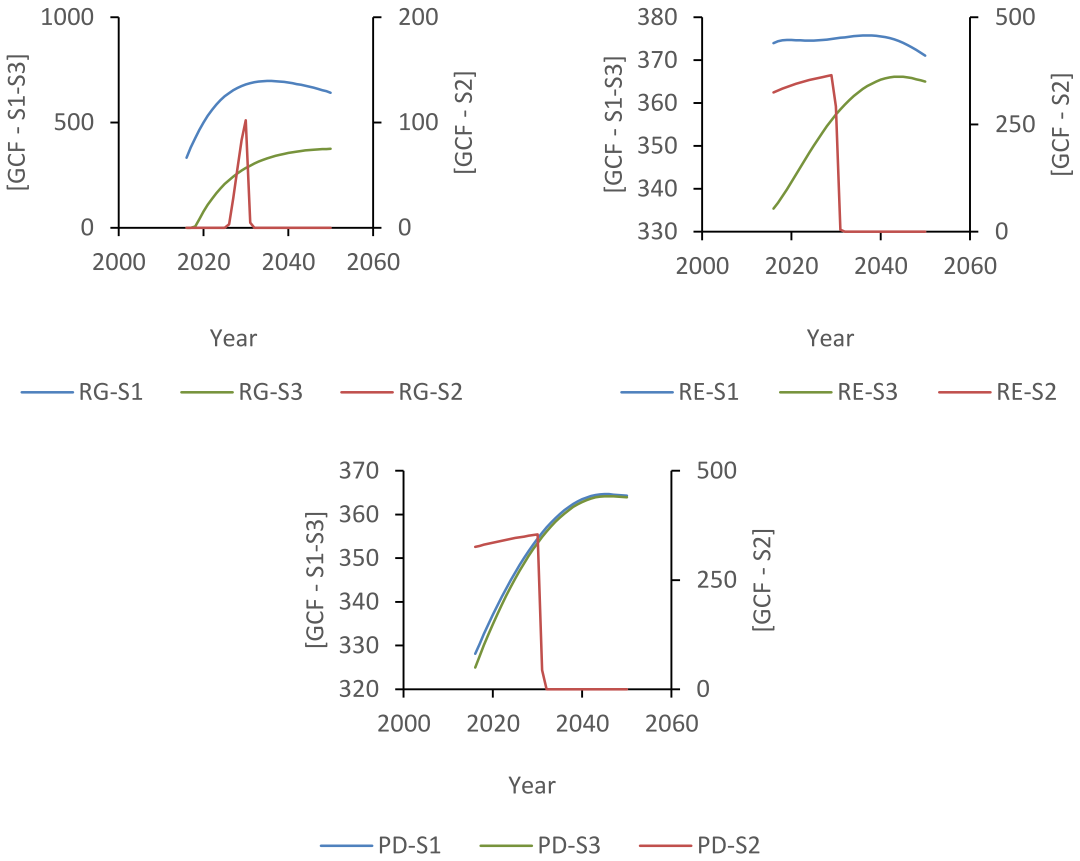


Figure 35. Behavior of end results in the natural gas supply chain model under three different scenarios

As performance measures of the supply chain, the reserve, production and transport margins are initially calculated (equations 38, 39 and 40), which show the behaviour of the relationship between supply and demand for each key actor involved in the chain. In scenario S2, there is a fall in the mentioned margins, which corresponds to the shortage given by higher values in the capacity generation times and low percentages of reliability (see Figure 32). In scenarios S1 and S3 there is no margin of shortage or it equals zero, and it is noteworthy that in the case of scenario S1 for all the stakeholders in the chain, a higher margin is observed than in scenario S3. Finally, the unmet demand *UM* (equation 41) is presented in scenario S2, reaching 363 [GCF] from year 2032 (see Figure 36).

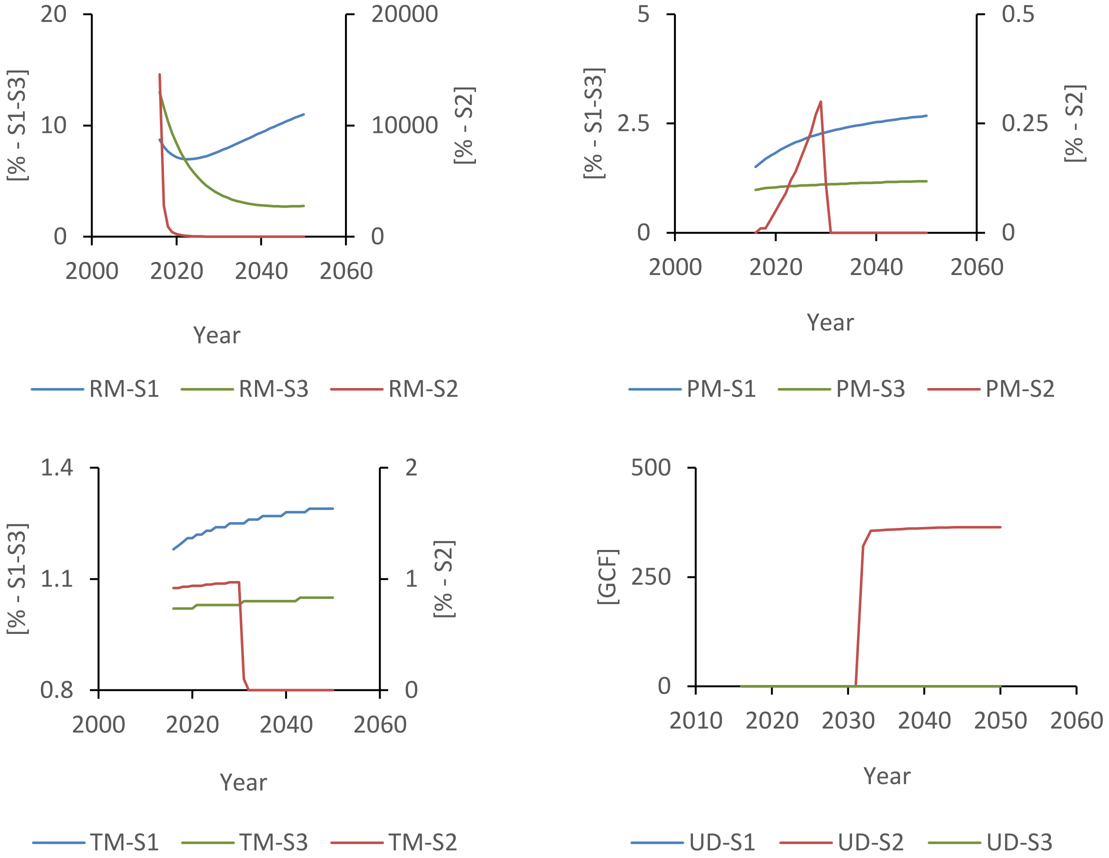


Figure 36. Behavior of margins and unmet demand in the natural gas supply chain model under three different scenarios

3.4 Concluding remarks

Natural gas as an energy source has certain advantages over conventional sources, such as ease of implementation of infrastructure (reserves, production and transport), lower supply cost, lower environmental impact, ease of transportation by ships or pipelines, among others.

In the review of the literature it is highlighted that the investigations that apply the methodology of systems dynamics and in particular the Dynamic Performance Management (DPM) approach, have not addressed the problem of natural gas supply and especially as a supply chain, therefore, the model developed in this chapter is presented as a novel proposal for the analysis of the dynamic management of the performance of energy supply chains. Starting with the formulation of the dynamic hypothesis, detailed the causal loop diagram, the stocks and flows diagram, the mathematical model (including its validation), conduct the analysis and report of scenarios.

Through the instrumental view of Dynamic Performance Management (DPM), the most influential policy levers on performance drivers (requirements in the generation of capacity of the stakeholders in the chain) are identified, allowing the decision makers to anticipate the effects of the resources allocation, by generating infrastructure projects in the stakeholders (reserves, production and transport), for the policies application that, on the one hand, facilitates the attention of the demand and, on the other, does not generate idle capacities in the supply system key actors.

Three simulation scenarios have been explored up to year 2050. These combine implementation times (*TDR*, *TDE* and *TDC*) and reliability percentages as security stocks (*RR*, *PR* and *TR*), thus providing elements to the decision makers for the identification and prioritization of policies among the stakeholders of the chain, which enables to improve the performance in the supply of natural gas. Therefore, it is suggested that the regulator (national government) must set the mechanisms for the integration of the stakeholders or organizations that are part of the supply chain of natural gas, for the planning of the investment projects, the generation of infrastructure in the various key actors, and the allocation of resources for the reduction of the implementation times. This as a confirmation of the hypothesis raised in this research, related with the planning of the policies oriented to the improvement of the performance in the supply.

Thesis Conclusions

The aim of this dissertation has been to make a contribution to the field of energy supply problems related to supply public policies, with particular reference to Colombian natural gas system.

The first chapter of this thesis shows a first natural gas supply chain model, in which different actors are presented by means of the system dynamics methodology, as well as the effect of the consumer price on the generation of capacity. Through this chapter it is possible to contribute to the knowledge of the effect that occurs in the supply through the modification of variables that can be defined as controllable by the decision makers, in this case, the governmental entities responsible for regulation and budget allocation for infrastructure construction.

As an extension of the model developed in chapter one, a model is presented in chapter two that involves capacity in construction and built capacity for production and transportation levels, against the incentives effects or not of natural gas prices at the wellhead and the consumer. This gives more details of utility to public policymakers, who could identify implementation goals of capacity expansion projects, focused on guaranteeing attractive price levels for both chain suppliers and final consumers, without ignoring the timely and uninterrupted supply of natural gas.

In terms of guaranteeing the supply of natural gas mentioned, chapter three develops a supply chain model in which the demand of the next link determines the need for capacity generation of the link that precedes it. This is supported through the application of the Dynamic Performance Management (DPM), through which in a more structured way, the main police and levers are identified that allow achieving a better performance of the modeled supply chain, with the objective of reducing or eliminating the unmet demand in the system, which will require greater resources allocated to capacity expansion projects.

Through the literature review, the research conducted on the supply of energy and particularly natural gas is identified, delving into those that apply systems dynamics. Through this review it is detected that the problem of natural gas supply has not been addressed as a supply chain composed by several interacting actors or through systems dynamics modelling.

In this thesis is modeled in a novel way the supply chain of natural gas in Colombia using systems dynamics simulation. It involves various sectors that intervene in the supply chain, such as reserves, production, transport and demand. Through the analysis of scenarios, it is possible to observe the effect of relevant variables for the actors involved and the decision makers in public policy formulation, on the main objective of avoiding future shortages in the supply of natural gas in the country.

Through the simulation model, the effect of delays in the development of implementation projects on the generation of capacity in the actors and therefore in the system in general is observed, which increases the discrepancies between the supply needs and the capacity of each of the links in the chain, causing the "downstream" oscillations to increase the instability to efficiently meet the requirements of the "upstream" resource, as well as to affect the stabilization times of prices.

The modelling of the supply chain of natural gas through systems dynamics allows one to identify the speed at which capacity levels must be generated to build and already built, based on the demand requirements of the next link in the chain, added at a level of reliability that protects the system from variations in demand and considering the effects of the price at the mouth of the well above the levels of production and the price to the consumer on transport levels.

Dynamic Performance Management (DPM) contributes to the planning and improvement of the natural gas supply performance in Colombia, enabling to identify the capacity requirements for the chain's stakeholders, in which public policy decision-makers can opportunely act by intervening on the policy levers of greater influence on the performance drivers of the system, considering, on the one hand, attention in a balanced way to the demand of the different sectors of national consumption and, on the other, not generating excess idle capacity of the actors of the chain, which would impact the cost of supplying the energy resource.

Limitations and Future Perspectives

Some limitations for the development of this research center on the difficulty to obtain updated historical data. The data is reported in several units of measurement, which involves additional stages of validation prior to the development of the simulation models. In Colombia there is no centralized information, much of this is found in databases and reports of public and private actors around natural gas. Many of these difficulties were solved through the participation of the Sub-Directorate of Hydrocarbons of the Mining and Energy Planning Unit of Colombia (UPME).

A supply chain can be made up of many actors and in the case of the supply of natural gas it is not different, so to achieve a good representation of the real world and as it is presented in the Supply Chain Management (SCM) approach, chain actors were grouped into the main groups or links in the network, this associated with the limitation of finding information with a certain level of detail and disaggregation. However, it is considered that because they are novel models in the field of energy supply chain modeling, useful information is obtained for public policy makers (national government) and decision makers (private companies regulated by the government).

Related to the aforementioned, Sterman's argument [87] "all models are wrong" is highlighted, considering the omission of variables and stakeholder participation that may be key to the correct interpretation of the models, combined with the limitations derived from the ignorance about the political will, with respect to the implementation of natural gas supply policies, that together with infrastructure projects allow to generate the necessary supply capacity identified in this dissertation. However, we are optimistic that through the development of the models presented here, support tools for decision making and counterintuitive thinking are favored, which in the natural gas case, given their applications as energy source, benefits to the environment and its affordable low-cost, do not seek something different than the possibility of making a better world, because ultimately, that is the main objective of public policies.

Future research work will seek to guide the supply chain models in energy and using systems dynamics, in the migration of conventional energy sources to sustainable energy sources, especially in the Colombian case.

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Appendix

Appendix A. Chapter 1 iThink software (equations of the model)

Production_P(t) = Production_P(t - dt) + (Production_supply_PSP - Production_shipping_PS) * dt

INIT Production_P = 223.36

INFLOWS:

Production_supply_PSP = Production_capacity_PC*Effect_of_consumer_price_on_production_ECPP

OUTFLOWS:

Production_shipping_PS = Production_P/Time_for_capacity_construction_TCC

Transport_T(t) = Transport_T(t - dt) + (Production_shipping_PS - Attended_demand_AD) * dt

INIT Transport_T = 238.52

INFLOWS:

Production_shipping_PS = Production_P/Time_for_capacity_construction_TCC

OUTFLOWS:

Attended_demand_AD = Expected_demand_ED*Effect_of_consumer_price_on_demand_ECPD

Consumer_price_CP(t) = Consumer_price_CP(t - dt) + (Change_in_consumer_price_CCP) * dt

INIT Consumer_price_CP = Consumer_reference_price_CRP

INFLOWS:

Change_in_consumer_price_CCP = (Suggested_consumer_price_SCP-Consumer_price_CP)/Time_to_adjust_consumer_price_TACP

Expected_demand_ED(t) = Expected_demand_ED(t - dt) + (Changes_in_demand_CD) * dt

INIT Expected_demand_ED = 277.185142

INFLOWS:

Changes_in_demand_CD = Expected_demand_ED*Per_capita_demand_growth_PDG

Consumer_reference_price_CRP = 11.12

Desired_transport_DT = Attended_demand_AD*Transport_coverage_TC

Effect_of_consumer_price_on_demand_ECPD = GRAPH(Consumer_price_CP/Consumer_reference_price_CRP)

(0.25, 2.00), (0.5, 1.56), (0.75, 1.25), (1.00, 1.00), (1.25, 0.8), (1.50, 0.65), (1.75, 0.5), (2.00, 0.4), (2.25, 0.3), (2.50, 0.21), (2.75, 0.15), (3.00, 0.1)

Effect_of_consumer_price_on_production_ECPP = GRAPH(Consumer_price_CP/Consumer_reference_price_CRP)

(0.25, 0.1), (0.5, 0.49), (0.75, 0.77), (1.00, 1.00), (1.25, 1.20), (1.50, 1.36), (1.75, 1.50), (2.00, 1.65), (2.25, 1.75), (2.50, 1.85), (2.75, 1.94), (3.00, 2.00)

Effect_of_transport_margin_on_price_ETMP = GRAPH(Transport_margin_TM)

(0.25, 2.00), (0.525, 1.80), (0.8, 1.55), (1.08, 1.35), (1.35, 1.15), (1.63, 1.00), (1.90, 0.875), (2.18, 0.75), (2.45, 0.65), (2.73, 0.55), (3.00, 0.5)

Per_capita_demand_growth_PDG = GRAPH(TIME)

(2005, 0.0131), (2006, 0.0127), (2007, 0.0123), (2008, 0.0119), (2009, 0.0115), (2010, 0.011), (2011, 0.0106), (2012, 0.0102), (2013, 0.00984), (2014, 0.00948), (2015, 0.00915), (2016, 0.00883), (2017, 0.0085), (2018, 0.00817), (2019, 0.00783), (2020, 0.00748), (2021, 0.00713), (2022, 0.0068), (2023, 0.00647), (2024, 0.00615), (2025, 0.00585), (2026, 0.00554), (2027, 0.00524), (2028, 0.00495), (2029, 0.00466), (2030, 0.00438), (2031, 0.0041), (2032, 0.00382), (2033, 0.00355), (2034, 0.00327), (2035, 0.003), (2036, 0.00272), (2037, 0.00246), (2038, 0.00219), (2039, 0.00194), (2040, 0.00168), (2041, 0.00144), (2042, 0.00119), (2043, 0.00095), (2044, 0.000708), (2045, 0.000467), (2046, 0.000229), (2047, -1.64e-006), (2048, -0.000219), (2049, -0.00042), (2050, 0.00), (2051, -0.000607)

Production_capacity_PC = 163.1

Suggested_consumer_price_SCP = Consumer_price_CP*Effect_of_transport_margin_on_price_ETMP

Time_for_capacity_construction_TCC = 6

Time_to_adjust_consumer_price_TACP = 1/12

Transport_coverage_TC = 1+(0.24)

Transport_margin_TM = Transport_T/Desired_transport_DT

Appendix B. Chapter 2 iThink software (equations of the model)

Production_P(t) = Production_P(t - dt) + (Production_capacity_constructed_PCC - Production_deliveries_PD) * dt

INIT Production_P = 223.36

INFLOWS:

Production_capacity_constructed_PCC = Production_under_construction_PUC/Construction_time_in_production_PTT

OUTFLOWS:

Production_deliveries_PD = Desired_transport_DT*((Effect_of_consumer_price_on_transport_ECPT+Effect_of_wellhead_price_on_transport_EWPT)/2)

Production_under_construction_PUC(t) = Production_under_construction_PUC(t - dt) + (Reserves_extraction_RE - Production_capacity_constructed_PCC) * dt

INIT Production_under_construction_PUC = Production_P

INFLOWS:

Reserves_extraction_RE = Reserves_generation_RG*Effect_of_wellhead_price_on_production_EWPP

OUTFLOWS:

Production_capacity_constructed_PCC = Production_under_construction_PUC/Construction_time_in_production_PTT

Reserves_R(t) = Reserves_R(t - dt) + (-Reserves_extraction_RE) * dt

INIT Reserves_R = 8044.491

OUTFLOWS:

Reserves_extraction_RE = Reserves_generation_RG*Effect_of_wellhead_price_on_production_EWPP

Transport_T(t) = Transport_T(t - dt) + (Transport_capacity_constructed_TCC - Attended_demand_AD) * dt

INIT Transport_T = 238.52

INFLOWS:

Transport_capacity_constructed_TCC = Transport_under_construction_TUC/Construction_time_in_transport_CTT

OUTFLOWS:

Attended_demand_AD = Expected_demand_ED*Effect_of_consumer_price_on_demand_ECPD

Transport_under_construction_TUC(t) = Transport_under_construction_TUC(t - dt) + (Production_deliveries_PD - Transport_capacity_constructed_TCC) * dt

INIT Transport_under_construction_TUC = Transport_T

INFLOWS:

Production_deliveries_PD = Desired_transport_DT*((Effect_of_consumer_price_on_transport_ECPT+Effect_of_wellhead_price_on_transport_EWPT)/2)

OUTFLOWS:

Transport_capacity_constructed_TCC = Transport_under_construction_TUC/Construction_time_in_transport_CTT

Consumer_price_CP(t) = Consumer_price_CP(t - dt) + (Change_in_consumer_price_CCP) * dt

INIT Consumer_price_CP = Consumer_reference_price_CRP

INFLOWS:

Change_in_consumer_price_CCP = (Suggested_consumer_price_SCP-Consumer_price_CP)/Time_to_adjust_consumer_price_TACP

Expected_demand_ED(t) = Expected_demand_ED(t - dt) + (Changes_in_demand_CD) * dt

INIT Expected_demand_ED = 277.185142

INFLOWS:

Changes_in_demand_CD = Expected_demand_ED*Per_capita_demand_growth_PDG

Wellhead_price_WP(t) = Wellhead_price_WP(t - dt) + (Change_in_wellhead_price_CWP) * dt

INIT Wellhead_price_WP = Wellhead_reference_price_WRP

INFLOWS:

Change_in_wellhead_price_CWP = (Suggested_wellhead_price_SWP-Wellhead_price_WP)/Time_to_adjust_wellhead_price_TAWP

Construction_time_in_production_PTT = 3

Construction_time_in_transport_CTT = 3

Consumer_reference_price_CRP = 11.12

Desired_production_DP = Production_deliveries_PD*Production_coverage_PC

Desired_transport_DT = Attended_demand_AD*Transport_coverage_TC

Effect_of_consumer_price_on_demand_ECPD = GRAPH(Consumer_price_CP/Consumer_reference_price_CRP)

(0.25, 2.00), (0.5, 1.56), (0.75, 1.25), (1.00, 1.00), (1.25, 0.8), (1.50, 0.65), (1.75, 0.5), (2.00, 0.4), (2.25, 0.3), (2.50, 0.21), (2.75, 0.15), (3.00, 0.1)

Effect_of_consumer_price_on_transport_ECPT = GRAPH(Consumer_price_CP/Consumer_reference_price_CRP)

(0.25, 0.1), (0.5, 0.49), (0.75, 0.77), (1.00, 1.00), (1.25, 1.20), (1.50, 1.36), (1.75, 1.50), (2.00, 1.65), (2.25, 1.75), (2.50, 1.85), (2.75, 1.94), (3.00, 2.00)

Effect_of_production_margin_on_price_EPMP = GRAPH(Production_margin_PM)

(0.5, 2.00), (0.6, 1.80), (0.7, 1.55), (0.8, 1.35), (0.9, 1.15), (1.00, 1.00), (1.10, 0.875), (1.20, 0.75), (1.30, 0.65), (1.40, 0.55), (1.50, 0.5)

Effect_of_transport_margin_on_price_ETMP = GRAPH(Transport_margin_TM)

(0.25, 2.00), (0.525, 1.80), (0.8, 1.55), (1.08, 1.35), (1.35, 1.15), (1.63, 1.00), (1.90, 0.875), (2.18, 0.75), (2.45, 0.65), (2.73, 0.55), (3.00, 0.5)

Effect_of_wellhead_price_on_production_EWPP = GRAPH(Wellhead_price_WP/Wellhead_reference_price_WRP)

(0.25, 0.1), (0.5, 0.49), (0.75, 0.77), (1.00, 1.00), (1.25, 1.20), (1.50, 1.36), (1.75, 1.50), (2.00, 1.65), (2.25, 1.75), (2.50, 1.85), (2.75, 1.94), (3.00, 2.00)

Effect_of_wellhead_price_on_transport_EWPT = GRAPH(Wellhead_price_WP/Wellhead_reference_price_WRP)

(0.25, 2.00), (0.5, 1.56), (0.75, 1.25), (1.00, 1.00), (1.25, 0.8), (1.50, 0.65), (1.75, 0.5), (2.00, 0.4), (2.25, 0.3), (2.50, 0.21), (2.75, 0.15), (3.00, 0.1)

Per_capita_demand_growth_PDG = GRAPH(TIME)

(2005, 0.0131), (2006, 0.0127), (2007, 0.0123), (2008, 0.0119), (2009, 0.0115), (2010, 0.011), (2011, 0.0106), (2012, 0.0102), (2013, 0.00984), (2014, 0.00948), (2015, 0.00915), (2016, 0.00883), (2017, 0.0085), (2018, 0.00817), (2019, 0.00783), (2020, 0.00748), (2021, 0.00713), (2022, 0.0068), (2023, 0.00647), (2024, 0.00615), (2025, 0.00585), (2026, 0.00554), (2027, 0.00524), (2028, 0.00495), (2029, 0.00466), (2030, 0.00438), (2031, 0.0041), (2032, 0.00382), (2033, 0.00355), (2034, 0.00327), (2035, 0.003), (2036, 0.00272), (2037, 0.00246), (2038, 0.00219), (2039, 0.00194), (2040, 0.00168), (2041, 0.00144), (2042, 0.00119), (2043, 0.00095), (2044, 0.000708), (2045, 0.000467), (2046, 0.000229), (2047, -1.64e-006), (2048, -0.000219), (2049, -0.00042), (2050, 0.00), (2051, -0.000607)

Production_coverage_PC = 1+(0.1416*Construction_time_in_production_PTT)

Production_margin_PM = Production_P/Desired_Production_DP

Reserves_generation_RG = 189.45

Suggested_consumer_price_SCP = Consumer_price_CP*Effect_of_transport_margin_on_price_ETMP

Suggested_wellhead_price_SWP = Wellhead_price_WP*Effect_of_production_margin_on_price_EPMP

Time_to_adjust_consumer_price_TACP = 0.25

Time_to_adjust_wellhead_price_TAWP = 0.25

Transport_coverage_TC = 1+(0.0614*Construction_time_in_transport_CTT)

Transport_margin_TM = Transport_T/Desired_transport_DT

Wellhead_reference_price_WRP = 2.36

Appendix C. Chapter 3 iThink software (equations of the model)

Perceived_demand_D(t) = Perceived_demand_D(t - dt) + (Changes_in_demand_CD) * dt

INIT Perceived_demand_D = 277.185142

INFLOWS:

Changes_in_demand_CD = Per_capita_demand_growth_PDG*Perceived_demand_D

Production_P(t) = Production_P(t - dt) + (Reserves_extraction_RE - Production_deliveries_PD) * dt

INIT Production_P = 223.36

INFLOWS:

Reserves_extraction_RE = Required_extraction_capacity_REC

OUTFLOWS:

Production_deliveries_PD = Required_production_capacity_RPC

Reserves_R(t) = Reserves_R(t - dt) + (Reserves_generation_RG - Reserves_extraction_RE) * dt

INIT Reserves_R = 8044.491

INFLOWS:

Reserves_generation_RG = Required_reserves_capacity_RRC

OUTFLOWS:

Reserves_extraction_RE = Required_extraction_capacity_REC

Transport_T(t) = Transport_T(t - dt) + (Production_deliveries_PD - Consumption_C) * dt

INIT Transport_T = 238.52

INFLOWS:

Production_deliveries_PD = Required_production_capacity_RPC

OUTFLOWS:

Consumption_C = Perceived_demand_D

Desired_production_DP = Transport_T*(1+Production_reliability_PR)

Desired_reserves_DR = Production_P*(1+Reserves_reliability_RR)

Desired_transport_DT = Perceived_demand_D*(1+Transport_reliability_TR)

Per_capita_demand_growth_PDG = GRAPH(TIME)

(2005, 0.0579), (2006, 0.0127), (2007, 0.0123), (2008, 0.0119), (2009, 0.0115), (2010, 0.0111), (2011, 0.0107), (2012, 0.0102), (2013, 0.00986), (2014, 0.0095), (2015, 0.00916), (2016, 0.00884), (2017, 0.00851), (2018, 0.00818), (2019, 0.00784), (2020, 0.00749), (2021, 0.00715), (2022, 0.00681), (2023, 0.00648), (2024, 0.00617), (2025, 0.00586), (2026, 0.00555), (2027, 0.00525), (2028, 0.00496), (2029, 0.00467), (2030, 0.00439), (2031, 0.00411), (2032, 0.00383), (2033, 0.00356), (2034, 0.00328), (2035, 0.00301), (2036, 0.00274), (2037, 0.00247), (2038, 0.0022), (2039, 0.00195), (2040, 0.00169), (2041, 0.00145), (2042, 0.0012), (2043, 0.00096), (2044, 0.000718), (2045, 0.000477), (2046, 0.000239), (2047, 8.23e-006), (2048, -0.00021), (2049, -0.000411), (2050, -1.8e-005), (2051, -0.000581)

Production_adjustment_PA = (Desired_production_DP-Production_P)/Time_to_developed_extraction_TDE

Production_margin_PM = IF(Transport_T<=0)

THEN(0)

ELSE(Production_P/Transport_T)

Production_reliability_PR = 0.4

Required_extraction_capacity_REC = Transport_T+Production_adjustment_PA

Required_production_capacity_RPC = Perceived_demand_D+Transport_adjustment_TA

Required_reserves_capacity_RRC = Production_P+Reserves_adjustment_RA

Reserves_adjustment_RA = (Desired_reserves_DR-Reserves_R)/Time_to_developed_reserves_TDR

Reserves_margin_RM = IF(Production_P<=0)

THEN(0)

ELSE(Reserves_R/Production_P)

Reserves_reliability_RR = 0.15

Time_to_developed_extraction_TDE = 6

Time_to_developed_reserves_TDR = 20

Time_to_developed_transport_TDC = 6

Transport_adjustment_TA = (Desired_transport_DT-Transport_T)/Time_to_developed_transport_TDC

Transport_margin_TM = IF(Perceived_demand_D<=0)

THEN(0)

ELSE(Transport_T/Perceived_demand_D)

Transport_reliability_TR = 0.3

Unmet_demand_UD = Perceived_demand_D-Consumption_C