IBP1321_13

TECHNICAL AND ECONOMICS STUDY FOR THE EXPANSION OF THE GASMIG PIPELINE

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Abstract
PUC-Rio/SIMDUT and GASMIG developed a technical and economic study for the expansion of the pipeline São Brás do Suaçuí (SBS) – Belo Oriente (BO), through thermo hydraulic simulations and economic calculations. The objective was to analyze and propose possibilities to increase the transport capacity of the pipeline for specific demands scheduled for 2015, 2017 and 2022, doing economic and technical comparisons of different possibilities.
To make sure that the optimal economic solution for the problem is found, the methodology was developed dividing the problem in two steps, called preliminary and detailed. The first one was designed to analyze a bigger number of different solutions, filtering a big number of very different solutions to some winner cases and was applied only to the 2022 scenario. The second one (detailed) is then applied to the winner cases of the preliminary step. Two cases were chosen to be studied in details, with real budgets and with the analysis of the possibilities to meet the demands of the intermediary scenarios (2015 and 2017). The economics was checked and the best solution was selected.
After this preliminary stage, two cases were chosen to be studied in details, with real budgets and with the analysis of the possibilities to meet the demands of the intermediary scenarios (2015 and 2017). It was used a commercial pipeline simulator software to perform this analysis. A numerical model developed to represent actual situation was tuned with real operational conditions. For each case, the model was upgraded with the alternatives selected for each year and a precise thermo hydraulic solution was obtained. The economics were checked and the best solution was found.

1. Introduction

When contacted by GASMIG to study and project the increase of capacity of their pipeline, SIMDUT knew this would require a new technical and economic methodology to be done. This was developed from the beginning of the project throughout the execution of it the real case studied.
The studied pipeline is operated by GASMIG and is in full operation since 2009. It has 317,9km, without the branch lines and is composed by an initial section of 16'', followed by a section of 18'' and a third of 16''. For the initial conditions of the project, the pipeline has the capacity to transport 2,4 millions of cubic meters per day. The black elements of Figure 3 presents a flowchart diagram of the system, with details like length of sections, diameters and minimum pressures for the future condition.
A gas pipeline is designed for a determined capacity with a forecast of the future gas market of the region where it will be built. Eventually, after some years of operations, these systems require an increase on their capacity to deliver more gas to old delivery points or even to attend new delivery points. This can be done by adding new compression stations, loops or both to the system. Infinite possibilities can meet the new flow demand, but choosing the best economic alternative requires a methodology and study. The desired increase in capacity was informed by GASMIG and was organized on three different stages: 2015, 2017 and 2022. So, the main objective was to analyze and propose possibilities to increase the transport capacity of the pipeline for specific demands scheduled for these future scenarios (2015, 2017 and 2022), doing economic and technical comparisons of the different possibilities.
In order to evaluate the possibilities for expansion of the system, a methodology was developed to choose seven cases

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that technically attend the last demand (2022). These are consisted by new different combinations of loops and compression stations to the system, with different locations and sizes. A software was developed by SIMDUT to help in this process of the preliminary comparison between the cases, called GASPEX. This software brings together the hydraulic simulation of steady states results with the approximate economic results of capital expenditure and operational expenditure.
After this preliminary stage, two cases were chosen to be studied in details, with real budgets and with the analysis of the possibilities to meet the demands of the intermediary scenarios (2015 and 2017). It was used a commercial pipeline simulator software to perform this analysis. A numerical model developed to represent actual situation, was tuned with real operational conditions. For each case, the model was upgraded with the alternatives selected for each year and a precise thermo hydraulic solution obtained. The economics was checked and the best solution was selected.

2. Objectives

This project was developed in four different objectives, as presented in this paper on the following items:

3. Develop a preliminary technical and economic methodology to evaluate different solutions for the problem;

4. Apply the preliminary methodology to the real problem of GASMIG;

5. Develop a detailed technical and economic methodology to evaluate the winner cases of the preliminary study;

6. Apply the detailed methodology to the real problem of GASMIG..

3. Preliminary Technical and Economic Methodology

At this point of the work of sizing an increase of capacity on a gas pipeline system, it is intended to analyze the bigger number of cases that solve the problem as possible. For that, the first thing to do is define the cases that will be simulated and studied during the preliminary step of the project. These cases must cover the main different combinations of loops and compression stations as possible, without great concern on the details of the sizing.
After that, it is necessary to evaluate, through a technical and economic study, each one of them. Hydraulic simulations are required to size the loops and compression stations necessary to attend the expected demand and new contracts. Steady state simulations are enough for this objective. With the system sized, it is now necessary to evaluate which cases results on the smaller costs.
In order to automatize and make easier to size and evaluate a big number of cases, SIMDUT developed software called GASPEX. This tool calculates the steady state flow of the system, and so the hydraulic variables, and also the capital and operational costs involved (CAPEX and OPEX). The main objective of this tool is to determine the cost of the investment, respecting the technical conditions imposed to the system, like pressure limits of the pipeline and flow limits of the delivery points. The main characteristics implemented on GASPEX are listed below:

3.1. Technical Premises

In addition to the assumptions usually used on the analysis of typical natural gas flow on pipelines, such as one-dimensional, single phase and Newtonian flow, the following premises were defined to be used on the preliminary step of the complete study: Steady state flow; Isothermal flow; State equations: Peng-Robinson and Soave-Redlich-Kwong; Colebrook friction equation; Viscosity using the correlation of Lee et.al; Calorific power and K (Cp/Cv) calculated using the state equation; Equipment and elements available: Supply point, Delivery point, Control valve, Compression station, Pipeline, Friction equations available: Weymoth, Colebrook, Panhandle-A and Panhandle-B, IGT, AGA-A and AGA-B, Spatial discretization uniform for the pipeline (knot spacing), Generic compressors with adiabatic efficiency, Elevation provided on the delivery and supply points, Reference conditions for the volume calculations: 20° and 1atm.

3.1.1. Thermodynamic properties

The most used state equations by the natural gas industry are the developed by Soave-Redlich-Kwong in 1972 and Peng-Robinson in 1976 (Pratt, 2002), for returning better results than the ideal gas law, mainly when submitted to high pressures and low temperature. These state equations estimate the behavior of the gases on any condition of pressure and temperature, including those close to the critic point, because they consider the intermolecular iterations. GASPEX permits the user to choose from these two equations, being Peng-Robinson the default.

Natural gas is formed by a combination of several chemical substances. In order to determine the state equations, it is necessary to define the properties of the mixture, which depends on the composition of the natural gas. The state equations need the properties of each pure substance that compose the gas natural. These properties are easily found on the literature (Van Wylen and Sonntag 2003).

Absolute viscosity is calculated using the Lee et al (1966) correlation, valid only for natural gas mixtures.

3.3. Equipment Properties

Generally, the application of conservation equations, when associated to equipment, requires the adoption of hypotheses or approximations associated with the kind of problem to be solved. The general hypotheses for the formulation of the problem are: Mass or volume balance as standard for the nodes; One-dimensional flow on steady state and isothermal; Empiric correlation based on the conservation of linear momentum and energy on therms of pressure an flow for each equipment.

3.1. Economic Premises

For the preliminary study, the economic calculations are done inside GASPEX, using the equating implemented on software and the costs input, together with the technical solutions found. This way, the capital expenditure (CAPEX) and operational expenditure (OPEX) are calculated directly from the technical solutions, allowing the user to evaluate and compare the costs of different technical solutions easily, by looking at the results of present costs obtained.

At this stage of the analysis of the problem, approximate costs are enough to be used for comparing the different cases. GASPEX automatically calculates costs per units such as quantity, time, length, and diameter.

Economic parameters such as interest rates and discount rates also need to be entered for the cash flow to be calculated. Present value is calculated for each technical solution through a simplified cash flow formed by a series of payments, using a fix tax G for the raises of costs and an interest rate J.

Partial present values are calculated for future values of CAPEX and OPEX on the period i according to the expressions below:

$$VPP_{CAPEX}(k) = \sum_{i}^{np} \frac{VF_{CAPEX}(i,k)}{(1+J)^i} \quad (1)$$

$$VPP_{OPEX}(m) = \sum_{i}^{n} \frac{VF_{OPEX}(i,m)}{(1+J)^i} \quad (2)$$

Where *np* represents the total number of periods of the cash flow;

The present value of the investment is the sum of all partial present values of CAPEX and OPEX:

$$VP = \sum_{k} VPP_{CAPEX}(k) + \sum_{m} VPP_{OPEX}(m) \quad (3)$$

Future expenditures can have their costs raised by a fix annual rate, *G*:

$$VF(i,m) = VF(s,m) \cdot (1+G)^{i-s}, i > s \quad (4)$$

4. Preliminary Study for 2022

GASMIG defined the average hourly flow of the delivery points for 2022. This is organized, along with the minimum pressure of the delivery points on Table 1.

Table 1. Average hourly flow (AHF) and minimum pressure of the delivery points for 2022

Delivery Point	AHF (m^3/h)	Minimum Pressure (kgf/cm^2)
DP1	44347	19
DP2	9593	10
DP3	1014	19
DP4	21	19
DP5	82531	19
DP6	1093	19
DP7	534	19
DP8	71	6
DP9	28039	12
DP10	27705	19
DP11	13393	10
DP12	88	6
DP13	56585	13
DP14	506	8
DP15	474	8
DP16	10327	10
DP17	1412	13

4.1. Costs

At the preliminary study, only the main costs involved were analyzed. The same premises and approximations were used for all the compared cases.

4.1.1 CAPEX

Some of the CAPEX costs were informed by GASMIG to SIMDUT, others were estimated with the experience of past projects. The CAPEX costs considered on the preliminary study are: Steel cost per weight,construction and assembly for different diameters, per length,compression stations (SCOMP) commissioning and installation.

4.1.2. OPEX Costs

The OPEX costs of the SCOMPs were calculated from previous budgets of GASMIG. The cost of the consumed gas on the compression stations was informed by GASMIG. The OPEX costs are: Rent of the SCOMPs; Operation and maintenance of the SCOMPs; Consumed gas.

4.2. Other Premises

Beside the premises of item 3, the following premises were considered for this specific preliminary study:

- Simplified gas composition;
- Maximum discharge pressure for SCOMPs 51kgf/cm²;
- Loop solutions projected using ASME 31.8 and API 5L, considering:

    - Project pressure of 51 kgf/cm²;
    - Material API 5L X70;
    - Location class 4 (FET = 0.4);
- All CAPEX items acquired on the first year;
- OPEX costs for 20 years;
- Discount rate of 11% p.y.
- Interest rate of 5% p.y.

4.3. Preliminary Simulations and results

Seven different technical and economic solutions were chosen to be studied by the preliminary methodology. Those were chosen to analyze solutions that are very different one from another, but still respecting the physical restrictions of the system, like maximum pressure and locations available for compression stations. Six of those consider a SCOMP on the beginning of the pipeline. That was necessary because the capacity scheduled for the years 2015 and 2017 require a SCOMP to be attended, and a loop would take more time to be built than the available.
The seventh case analyzed the possibility to attend all the demand scheduled for 2022 without any compression station on the system. This was a request from GASMIG.

Table 2. Cases studied

Case	SCOMPs	Km of Loops
1	02 (SBS+DP5)	65,6 (Ø16”)
2	02 (SBS+BCOCAIS)	27,6 (Ø18”)
3	01 (SBS)	93,9 (Ø18”)
4	03 (SBS+DP5+BCOCAIS)	0
5	04 (SBS+DP2+OUROPRETO+BCOCAIS)	0
6	04 (SBS+DP2+DP5+BCOCAIS)	0
7	0 Full loop	230,1 (Ø22’’)

All the cases were studied following the same methodology, applying SCOMPs and loop enough to attend the demand scheduled for 2022 without violating any minimum pressure or flow. On all cases that use loop, a study was conducted in order to determine the optimal economic diameter, length and location. For that, several simulations were ran on GASPEX and a J curve on cost x diameter was obtained for each one of these cases. Figure 1 illustrates the J curve for case 7.

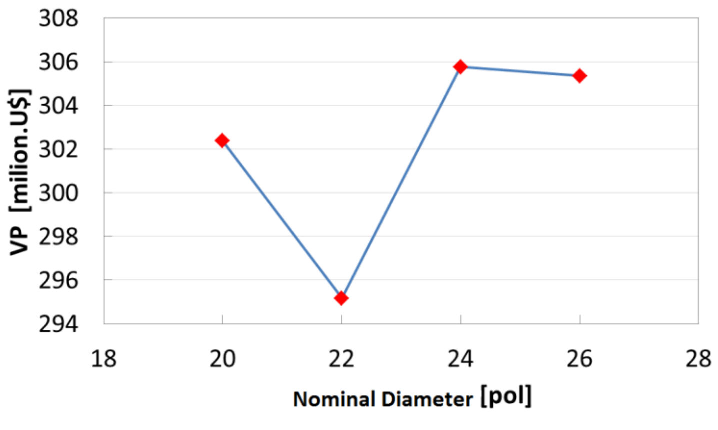

Figure 1. J curve of case 7

Table 3 shows the condensed results of the preliminary studies, and defines the winner cases.

Table 3. Preliminary Present Value Costs

Investment	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7
Total CAPEX	**93,992**	**62,843**	**109,906**	**53,700**	**71,600**	**71,600**	**295,176**
Total OPEX	**70,254**	**83,022**	**54,241**	**107,566**	**103,460**	**105,896**	**0**
VP [million US$]	**164,247**	**145,866**	**164,146**	**161,266**	**175,060**	**177,496**	**295,176**

For space conveniences, on this paper, only the two winner cases of the preliminary study will be presented:

4.3.1. Case 2

Case 2 consists of two SCOMPs and a loop with approximately 25,6km. The first SCOMP is located after the supply point, and the second one at B. COCAIS (located at ???). The loop has 18" of diameter and goes from SBS to DP5 (27.6km lenght).

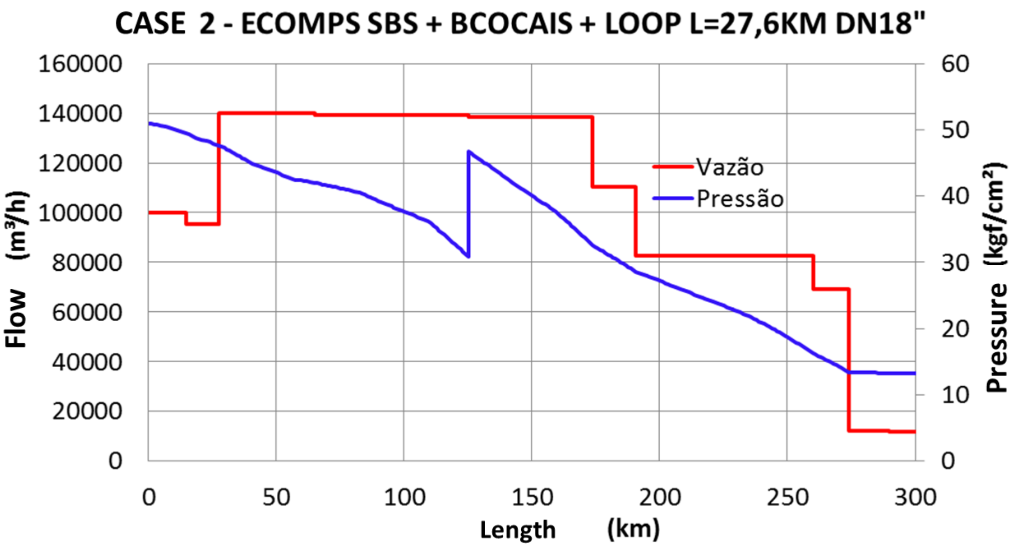

Figure 2. Hydraulic Gradient of Case 2

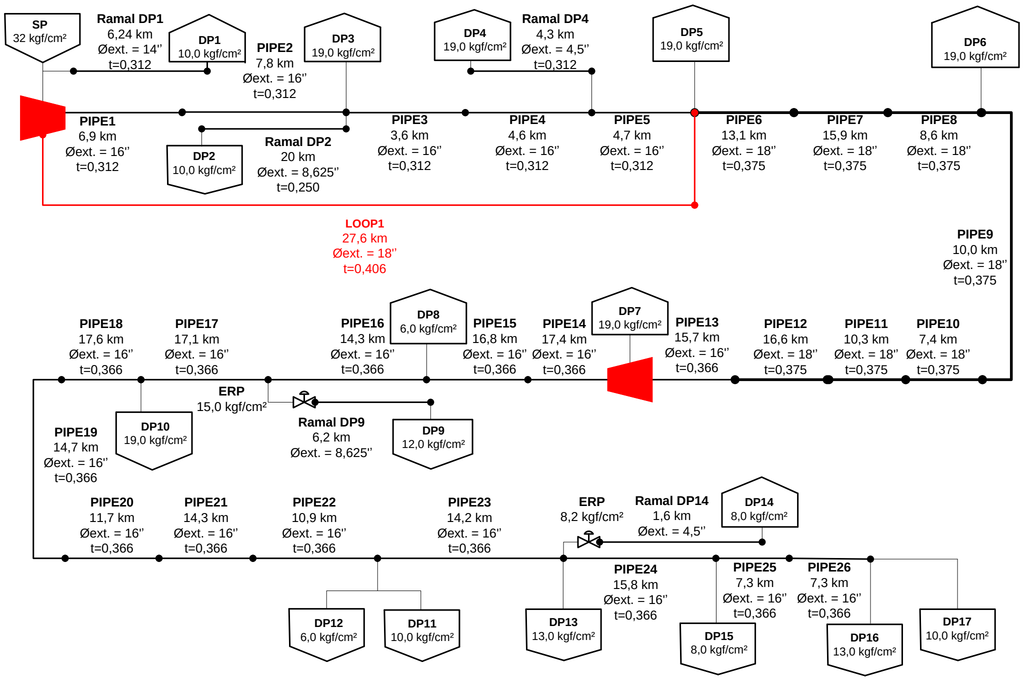

Figure 3. Flowchart of Case 2 for the preliminary study

4.3.1. Case 3

Case 3 consists on one SCOMP at the supply point and two separate loops, with a length of 93.9km. First loop has 27.6 km and 18''. Second loop has 66.3 km with 18'' of diameter and begins where the actual pipeline reduces from 18'' to 16''.

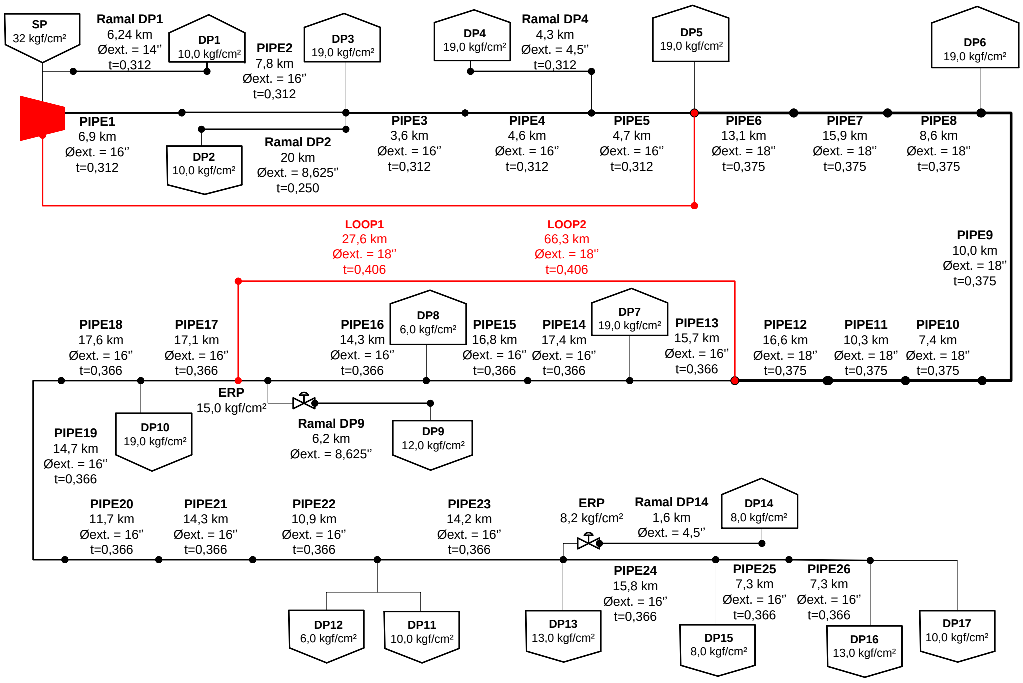

Figure 4. Flowchart of Case 3 for the preliminary study

4.5. Detailed Methodology

After the preliminary study, the alternatives for the increase of capacity are better known, and the two winner cases need now to be studied in a detailed form, in order to determine which the optimal technical and economic solution is.
For that, both cases are now simulated on commercial software for thermo hydraulic solutions. The economics of each one are now analyzed in details.

4.5.1. Detailed Methodology Premises

The premises for the thermo-hydraulic simulations include the usual: isothermal, one dimensional flow, monophasic and Newtonian fluid, Peng-Robinson state equation and Colebrook for friction calculus. Other technical premises are: all the SCOMPs utilizes the same efficiency value, all the pipelines have the same roughness, the pipeline operates in a steady state, with all the delivery points receiving the maximum contracted flow + 10% of flexibility, at the use rate specified by the client, no minimum pressure limit can be violated on the simulations, and the consumed gas on the compression stations are calculated by the software.
The economics study was developed adopting the following premises: all cases are evaluated comparing the present value of the project for the increase of capacity of each case, including CAPEX and OPEX costs. The economic study was performed for a period of 20 years after the implementation of the last intervention. All the costs informed by the client was used, and others was estimated through SIMDUT's experience. Capital investment are allocated before the inauguration of the product (loop or SCOMP), considering the time that takes to conclude the work. All calculation was done in US dollars, and conversions for other currency was fix and estimated at the beginning of the project. Interest rate was defined by the responsible for the project.

4.5.2. Cost Categories

On a conceptual project, normally the investment and operational costs are more detailed than on a preliminary study. It's evaluation is based on industry rates obtained from specialized literature, congresses, access to the detailed project of other companies and the previous SIMDUT experience on real costs of other projects.
The allocation of the costs is done following cost structure adopted and the level of detail it comprehends. The structure applied on this methodology is a very detailed and refined one, and is divided on three main categories: construction, operation and deactivation.

Construction costs include direct costs: expropriation and prepare of the pipeline track, pipeline materials, cathode protection, coating, construction and assembly, compression stations, materials, assembly and commissioning and auxiliary systems such as communications and SCADA. Engineering costs include projects, surveys, studies, environmental licensing, public auditions and management of the mitigate measures required of the license. It includes also the managing of the work, administrative services, services contracts, supervision, quality control and security requirements. Other costs include the forecast of physical or economic eventualities and the cost of the immobilized inventory on the pipeline.

Operational costs are divided on two main categories: variable and fix with the volume to be transported.
The variable cost normally considers only the cost of the consumed energy, from the power required for the operation, which is function of the flow of the pipeline. Fix costs include company costs and services costs and normally are divided into: operation, maintenance, technical support, administrative support.
Deactivation costs on Brazil are a responsibility of the company authorized for the operation of the pipeline, and must cover the deactivation respecting the environmental laws. This cost appears in the end of the pipeline life, and because of that, has very little impact on the present value of the project.
Some costs are not considered on this methodology of evaluation: connection to the electric grid, working capital, hiring and training of personal, legal and administrative costs, overhead for the operation and deactivation costs.
Economic comparison and calculation for the present value is done following the same equations present on item 3.1.

4.6. Detailed study results

After evaluation the preliminary results, GASMIG decided to fix the loops diameter on 22", because that would be the size chosen for a no compression solution, as shown on Figure 1. This was a strategic decision, based on the results that indicated that different diameters (and consecutively, lengths) represent small changes on the total cost of this project.
Cases 2 and 3 were chosen by GASMIG to be analyzed on two different solutions by 2017. The first one, called *a*, considers the construction of the first loop together with the first SCOMP. On the other hand, solution *b* considers no

loop by 2017, and so needs a higher discharge pressure at the first SCOMP to attend the new demand. Cases 2a, 2b, 3a and 3b were simulated and studied following the methodology described on item 3.Table 4 describes the solutions analyzed with the detailed methodology.

Table 4. Preliminary Present Value Costs

Scenarios	**Cases**	
	2	**3**
2015	SCOMP SBS ($P_{discharge}$ = 42,0 kgf/cm²)	
2017a	SCOMP SBS (P+ = 45,5 kgf/cm²) + 27,8 km Loop 22''	
2017b	SCOMP SBS (P+ = 51,0 kgf/cm²)	
2022	SCOMP SBS (P+ = 51,0 kgf/cm²) + 27,8 km Loop 22'' + SCOMP DP6 (P+ = 49,0 kgf/cm²)	SCOMP SBS (P+ = 51,0 kgf/cm²) + 27,8 km Loop 22'' + 22,0 km Loop 22''

It was possible to adjust the lengths of loops and location of the compression stations in a way that the solutions differ one from another only on 2022. This way, cases 2 and 3 have the same solutions until 2017. This permits also attending possible future variations on flows on 2017 and 2022 if the forecast market changes.

Investment	**Case 2a**	**Case 2b**	**Case 3a**	**Case 3b**
VP (million US$)	147,612	135,289	141,379	**128,940**

The *b* alternatives resulted on smaller present values. The complete cash flow with the income and expenses was done by GASMIG after this study.
Figure 5 shows the cash flow of case 3b, separated by items on each year. This was also the case chosen by gasmig after the complete cash flow study, including incomes.

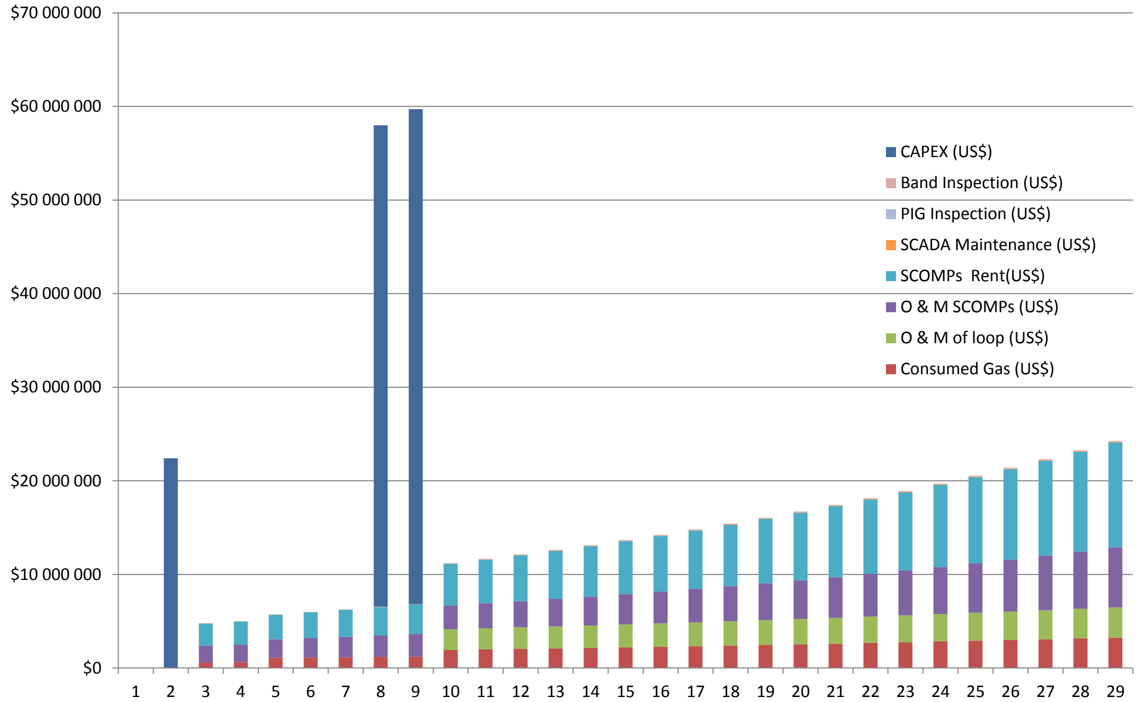

Figure 5. Cash flow of case 3b

5. Conclusions

This study helped to develop and tested a methodology created to find the optimal technical and economic solution for a increase in the capacity of a pipeline. Infinite technical solutions can attend a new flow demand on a pipeline, and finding the optimal requires filtering these into some cases to simulated. A preliminary methodology was created using approximate costs and a software that integrates the thermo hydraulic calculations with the economic results, in order to evaluate a big number of different cases. After this, a more detailed study is required, especially for the costs involved, in order to define the conceptual project, and the methodology developed has shown good results.

6. Acknowledgements

Acknowledgements to all SIMDUT and GASMIG team involved on this work.

7. References

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