POLITECNICO DI TORINO

Master of Science program in Energy and Nuclear Engineering

Energy Networks

DESIGN OF A GAS NETWORK SYSTEM

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Introduction

This work aims to design and simulated a municipal gas network – species 4. For this class of gas pipelines, the maximum and minimum operating pressure is 5 [bar-g] and 1.5 [bar-g], which belongs to a medium-pressure pipeline. The function of the pipeline is to connect the transmission infrastructure to end users.

The goal of this project:

1) Design of a natural gas network – SIZING PHASE

2) Fluid dynamic analysis of the network - SIMULATION PHASE

During the sizing phase, the design of the gas network and the city gate pressure-reducing station (ReMi) need to consider the following factors:

1. User requirements: it is needed to understand the user's gas consumption demands and basic information, including gas usage, gas pressure, gas equipment, etc.
2. Pipeline characteristics: it is necessary to understand the characteristics of the pipeline, such as materials, diameter, length, friction resistance coefficient, as well as the arrangement and connection of the pipeline branches.
3. ReMi station: we should determine the location and scale of the compressor station and ReMi station to ensure that the gas can maintain the required pressure during transportation.

After the design of the gas pipeline network is completed, simulation analysis is required to verify the correctness and feasibility of the design. During the simulation phase, the following parameters can be considered:

1. Different customer gas consumption: according to the different gas consumption demands of customers, load analysis of the gas pipeline network can be conducted to understand the operation of the pipeline under different gas consumption levels.
2. loop open and closed states: analysis of the gas pipeline network can be conducted according to the open and closed states of the pipeline branches to understand the impact of some branches' open and closed states on the pipeline network.
3. Different gas compositions: when analyzing the gas pipeline network, it is necessary to consider the gas composition to understand the impact of different gas compositions on the pipeline.

1) SIZING PHASE

Considering the Russo-Ukrainian War resulting in unreliable and un-sustained Gas Russo, we choose Gas Algerino as the supply gas in our project, which is almost the second largest supply source for IT. Some of the important parameters of the gas are shown in Table 1.

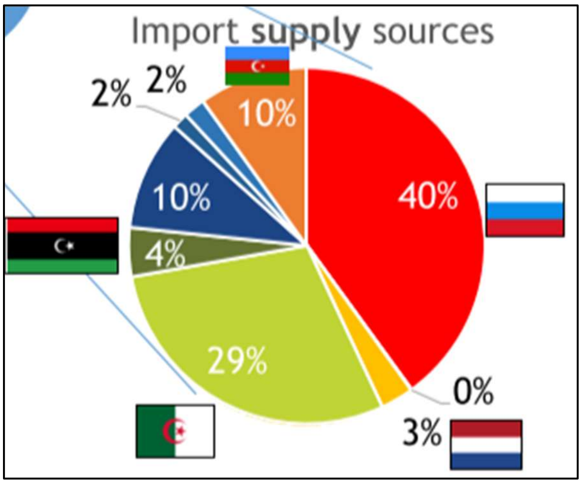

Figure 1. Italian Gas Supply in 2021

Table 1. gas parameters

Low heating value		Density
[kWh/Sm3]	[MJ/Sm3]	[kg/Sm3]
10.091	36.3276	0.78836

1. Determination of the gas demand

We have designed a gas network consisting of 30 branches, 31 nodes and 18 buildings according to the given design requirements. The parameters of each building are shown in Table 2 and the length of each branch is shown in Table 3.

The indoor and outdoor temperature in the design condition is 20°C and -8°C, separately. Then, we can calculate the heat demand of each building with the equation:

$$\Phi_d[kWh] = r \cdot V \cdot (T_{indoor,d} - T_{outdoor,d})$$

Regarding the boilers used for heating, Bosch components were selected, and boiler efficiencies were obtained from the product descriptions on the company's website. [Catalogo prodotti Bosch e listino prezzi | Bosch Clima (bosch-thermotechnology.com)] Then, the design mass flow rate and design volume flow rate can be calculated by the following equations:

$$\dot{Q}\left[\frac{Sm^3}{h}\right] = \frac{\Phi_d[kWh]}{\eta_{boiler} \cdot LHV\left[\frac{kWh}{Sm^3}\right]}$$

$$\dot{m}\left[\frac{kg}{h}\right] = \frac{\dot{Q}\left[\frac{Sm^3}{h}\right]}{\rho_n}$$

Table 2. buildings parameters

Building Number	Node Num	Building volume [m3]	Volumetric heat transfer coefficient	Boiler efficiency	Heat demand [kWh]	Volumetric flow rate [Sm3/h]	Mass flow rate [kg/h]
1 (old)	N8	260,000	0.9	0.88	7445	738	581.677
2 (old)	N6	200,000	0.9	0.9	5600	555	437.500
3 (old)	N7	320,000	0.9	0.85	9487	940	741.177
4 (old)	N10	190,000	0.9	0.93	5148	510	402.218
5 (old)	N12	170,000	0.9	0.9	4760	472	371.875
6 (new)	N14	180,000	0.4	0.94	2145	213	167.553
7 (new)	N15	220,000	0.4	0.94	2621	260	204.787
8 (new)	N17	140,000	0.4	0.95	1651	164	128.947
9 (new)	N18	100,000	0.4	0.94	1191	118	93.085
10 (old)	N20	330,000	0.9	0.8	10395	1030	812.110
11 (old)	N21	300,000	0.9	0.9	8400	832	656.251
12 (old)	N23	280,000	0.9	0.85	8301	823	648.530
13 (old)	N24	230,000	0.9	0.88	6586	653	514.560
14 (new)	N25	120,000	0.4	0.93	1445	143	112.903
15 (new)	N27	360,000	0.4	0.88	4582	454	357.955
16 (old)	N28	310,000	0.9	0.8	9765	968	762.891
17 (new)	N30	340,000	0.4	0.94	4051	401	316.490
18 (new)	N31	210,000	0.4	0.95	2476	245	193.421

Table 3. the length of branches

Branches	Connection	Length [m]	Branches	Connection	Length [m]
B1	N1-N2	1700	**B16**	N16-N17	2000
B2	N2-N3	1650	**B17**	N16-N18	1500
B3	N3-N4	1350	**B18**	N2-N19	3300
B4	N4-N8	1500	**B19**	N19-N20	700
B5	N4-N5	1900	**B20**	N19-N21	1400
B6	N5-N6	960	**B21**	N19-N22	2300
B7	N5-N7	1200	**B22**	N22-N23	900
B8	N4-N9	2300	**B23**	N22-N24	1100
B9	N9-N10	1000	**B24**	N22-N25	1450
B10	N9-N11	2500	**B25**	N2-N26	2200
B11	N11-N12	1100	**B26**	N26-N27	1300
B12	N11-N13	2400	**B27**	N26-N28	800
B13	N13-N14	1300	**B28**	N26-N29	1500
B14	N13-N15	1900	**B29**	N29-N30	1800
B15	N13-N16	2500	**B30**	N29-N31	1000

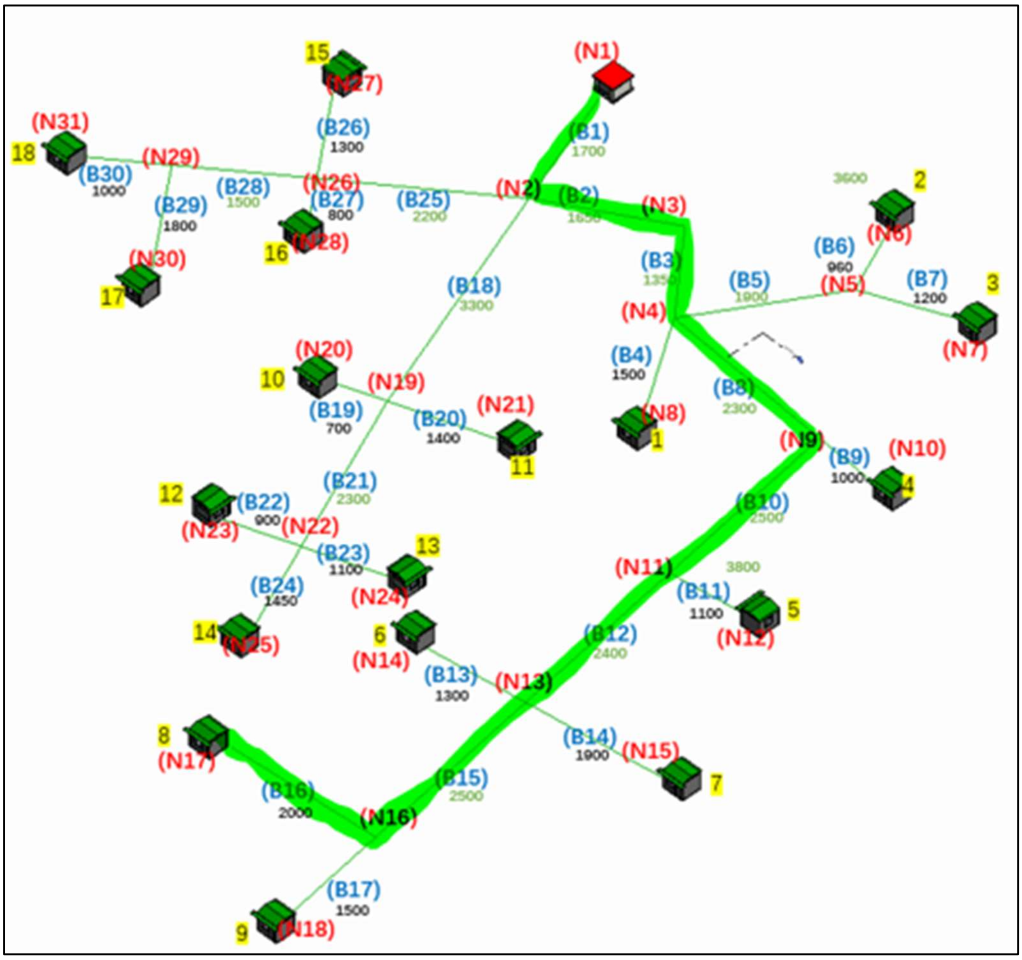

Figure 2. Topology of the gas network (without loop)

Here is the topology of the designed gas network system (without loop).

2. Sizing of the gas network

According to the data and figure 2, we can notice the path with the highest pressure drop (most stressed one) is: B1-B2-B3-B8-B10-B12-B15-B16. Then, we are going to determine the diameter of this line with the method of Fixing Linear Pressure Drop and the equations following. The results showed in the Table 5.

$$R_{RMP} = \frac{p_{in}^2 - p_{out}^2}{Q^{1.82} \cdot L}$$

$$D[m] = (5.20 \cdot 10^{-7} \cdot \frac{\rho_n}{\rho_{air}} \cdot \frac{1}{R_{RMP}})^{\frac{1}{4.82}}$$

$$\frac{p}{\rho} = z \frac{R_0}{MM} T$$

$$Q_{actual}\left[\frac{m^3}{s}\right] = \frac{\dot{m}\left[\frac{kg}{s}\right]}{\rho_{actual}\left[\frac{kg}{m^3}\right]}$$

$$Q_{actual}\left[\frac{m^3}{s}\right] = v\left[\frac{m}{s}\right] \cdot A[m^2]$$

Where:

D - pipeline diameter [m]

L - pipeline length [m]

Q – flow rate [Sm3/s]

R – fluid-dynamic resistance

Pin – inlet pressure (abs) [kg/cm2]

Pout – outlet pressure (abs) [kg/cm2]

ρ_{air} – standard air density [kg/m3]

ρ_n – standard gas density [kg/m3]

ρ_{actual} – gas density @ T, P

Moreover, we have to consider the concentrated pressure losses (local resistance) with the method: equivalent length.

Regarding the pressure at the inlet of the pipeline (N1), we assumed it as 5 bar (g) according to the Pipeline Classification (figure2), while the last outlet pressure at N17 is assumed as 1.6 bar(g).

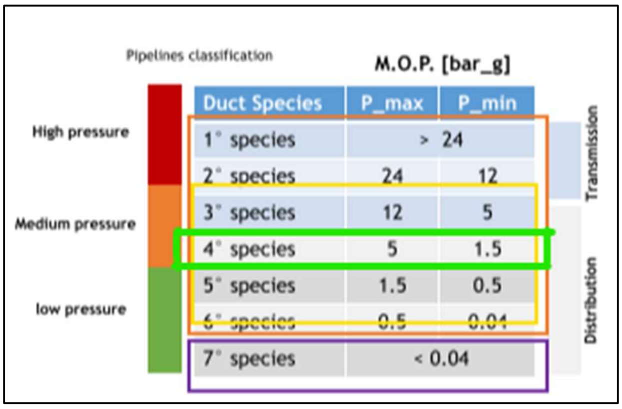

Figure 3. Pipeline Classification

Table 4. Parameters of the gas in the most stressed one

Branches List	B1	B2	B3	B8	B10	B12	B15	B16
Nodes link	N1-N2	N2-N3	N3-N4	N4-N9	N9-N11	N11-N13	N13-N16	N16-N17
Length[m]	1700.0	1650.0	1350.0	2300.0	2500.0	2400.0	2500.0	2000.0
Eq.Length[m]	13.0	4.5	13.0	6.5	6.5	13.0	6.5	0.0
Tot_Length[m]	1713.0	1654.5	1363.0	2306.5	2506.5	2413.0	2506.5	2000.0
Q[Sm3/s]	2.644	1.102	1.102	0.482	0.340	0.209	0.078	0.045
Pin(bar_g)	5.000	4.646	4.305	4.023	3.547	3.029	2.531	2.013
Pout(bar_g)	4.646	4.305	4.023	3.547	3.029	2.531	2.013	1.600
Pin(bar_a)	6.013	5.659	5.318	5.036	4.560	4.042	3.544	3.026
Pout(bar_a)	5.659	5.318	5.036	4.560	4.042	3.544	3.026	2.613
deltaP(bar)	0.354	0.342	0.281	0.476	0.518	0.498	0.518	0.413
Pin(kg/cm2)	6.132	5.771	5.423	5.136	4.650	4.122	3.614	3.086
Pout(kg/cm2)	5.771	5.423	5.136	4.650	4.122	3.614	3.086	2.665
R_RMP	0.000	0.002	0.002	0.008	0.013	0.028	0.146	0.336
D(mm)	226.78	165.08	167.09	124.22	111.42	95.19	67.62	56.85
A(m2)	0.040	0.021	0.022	0.012	0.010	0.007	0.004	0.003
P_m(bara)	5.836	5.489	5.177	4.798	4.301	3.793	3.285	2.820

rho_actual(kg/m3)	4.539	4.268	4.026	3.731	3.345	2.950	2.555	2.193
m_dot(kg/s)	2.084	0.869	0.869	0.380	0.268	0.165	0.062	0.036
Q_actual(m3/s)	0.459	0.204	0.216	0.102	0.080	0.056	0.024	0.016
velocity(m/s)	11.38	9.52	9.85	8.41	8.23	7.87	6.73	6.44
Max velocity check	✔	✔	✔	✔	✔	✔	✔	✔
Nominal Diameter	DN300	DN200	DN200	DN150	DN125	DN100	DN80	DN65

After getting the velocity of these branches, we have to check whether it is in the velocity range at a specific pressure. In this calculation, all the values are satisfied with the limit.

In the same way, the parameters of the whole network can be calculated. And finally, determine the nominal (commercial) diameter.

Then, in order to enhance the reliability and flexibility of the gas network, we are going to create two loops by adding two branches into the system: B31 from N19 to N29 and B32 from N22 to N16 shown in the following figure.

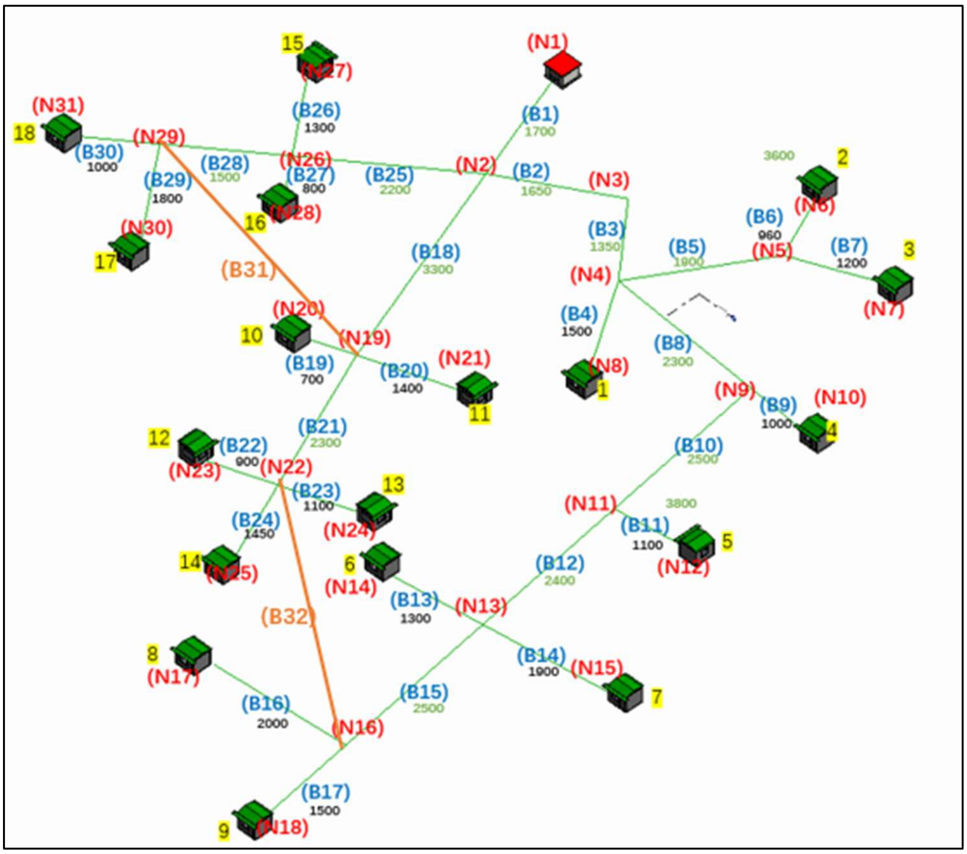

Figure 4. Topology of the gas network (with loop)

3. Sizing the ReMi station

In the ReMi station, gas will undergo a pressure reduction and the gas flow rate is generally measured.

During the pressure reduction the gas flow temperature decrease, but the temperature of the gas after the reduction must be regulated at an average value of 5 °C and in any case cannot be lower than 0 °C. To avoid this problem, it is installed a heat exchanger which preheats this gas flow rate to a proper temperature. Moreover, the piping system and the reduction valve needs also to be designed.

The constraints used to size the ReMi station:

Upstream Pressure P_1 = 50 [bar_a]

Upstream Temperature T_1 = 5 [°C]

Downstream Pressure P_2 = 6 [bar_a]

Downstream Temperature T_2 = 5 [°C]

$\eta_{preheater}$ = 0.9

η_{boiler} = 0.9

To proceed with the heating, the heat quantity supplied to each gas [kg] to increase the temperature from T1 to T2 must be determined.

With the 'PRESSURE – ENTHALPY FOR THE NATURAL GAS DIAGRAM', we can determine:

the enthalpy before gas preheater H_b @ P = 50 bar_a, T = 5 °C equals to 70 [kJ/kg] and

the enthalpy after gas preheater H_a @ P = 5 bar_a, T = 5 °C equals to 123 [kJ/kg].

Now the thermal needs are obtained by the formula bellow equals to 490997.9 [kJ/h] or 136.39 [kW].

$$\mathrm{M} = \frac{h * \rho_n * Q}{\eta_{boiler} * \eta_{preheater}}$$

$$Q_{gas\_preheater} = \frac{M}{\mathrm{LHV}}$$

The gas consumption of the preheater equals 13.52 [m3/h].

Then it comes to determine the pipeline size with an assumption Q_imp = Q_lin, with applying the equation bellow, the valve Dteo = 110.2 [mm], considering the DN ≥ 0.95Dteo, the pipe size selected at the upstream side is DN125.

$$\mathrm{Dteo} = \sqrt{\frac{345.92 * Q * (1 - 0.002 * P)}{v * (1 + P)}}$$

Where:

V – speed [m/s] (25)

P – relatively pressure in bar

Finally, it is the sizing for the reduction valve, with the fellow formula Cg equal to 10218.75, then the flow rate of the valve Q = 281015.6 m3/h

C_g = 0.6540*DN^2 (for DN up to 150 included)

Q = 0.55*C_g*P1 (with (P1-P2) ≥0.456P1)

2) SIMULATION PHASE

In this part, we are going to use MARLAB to do a simulation based on the SIMPLE algorithm which provides a robust approach for calculating pressures and velocities (mass flow rates in our case) combined with the Fixed-Point method for non-linear equation solving.

Here is some input data for our simulation regarding the information on branches and nodes, respectively.

Table 6. Branches and nodes info input for SIMPLE

Branches							Nodes		
Branches List	in	out	D [mm]	L [m]	Epsi [mm]	G [kg/s]	Nodes List	G_ext	Pressure [bar-a]
1	1	2	300	1700	0.01	2.084	1	-2.084	6
2	2	3	200	1650	0.01	2.084	2	0.000	6
3	3	4	200	1350	0.01	2.084	3	0.000	6
4	4	8	80	1500	0.01	2.084	4	0.000	6
5	4	5	125	1900	0.01	2.084	5	0.000	6
6	5	6	80	960	0.01	2.084	6	0.122	6
7	5	7	100	1200	0.01	2.084	7	0.206	6
8	4	9	150	2300	0.01	2.084	8	0.162	6
9	9	10	65	1000	0.01	2.084	9	0.000	6
10	9	11	150	2500	0.01	2.084	10	0.112	6
11	11	12	80	1100	0.01	2.084	11	0.000	6
12	11	13	125	2400	0.01	2.084	12	0.103	6
13	13	14	65	1300	0.01	2.084	13	0.000	6
14	13	15	80	1900	0.01	2.084	14	0.047	6
15	13	16	80	2500	0.01	2.084	15	0.057	6
16	16	17	80	2000	0.01	2.084	16	0.000	6
17	16	18	65	1500	0.01	2.084	17	0.036	6
18	2	19	200	3300	0.01	2.084	18	0.026	6
19	19	20	80	700	0.01	2.084	19	0.000	6
20	19	21	100	1400	0.01	2.084	20	0.226	6
21	19	22	125	2300	0.01	2.084	21	0.182	6
22	22	23	100	900	0.01	2.084	22	0.000	6
23	22	24	100	1100	0.01	2.084	23	0.180	6
24	22	25	65	1450	0.01	2.084	24	0.143	6
25	2	26	150	2200	0.01	2.084	25	0.031	6
26	26	27	80	1300	0.01	2.084	26	0.000	6
27	26	28	80	800	0.01	2.084	27	0.099	6
28	26	29	100	1500	0.01	2.084	28	0.212	6
29	29	30	80	1800	0.01	2.084	29	0.000	6
30	29	31	65	1000	0.01	2.084	30	0.088	6
31	19	29	200	4100	0.01	2.084	31	0.054	6
32	22	16	250	3800	0.01	2.084			

After the iteration to make the 'error' value under the tolerance that was set before, we got the result:

Table 7. Result from simulation

Branches		Nodes		
Branches List	G [kg/s]	Nodes List	Pressure [bar_a]	Pressure [bar_g]
1	2.084	1	6.00	5.00
2	0.852	2	5.93	4.93

3	0.852	3	5.84	4.84
4	0.162	4	5.76	4.76
5	0.327	5	5.57	4.57
6	0.122	6	5.43	4.43
7	0.206	7	5.42	4.42
8	0.363	8	5.40	4.40
9	0.112	9	5.65	4.65
10	0.251	10	5.31	4.31
11	0.103	11	5.58	4.58
12	0.148	12	5.46	4.46
13	0.047	13	5.52	4.52
14	0.057	14	5.43	4.43
15	0.044	15	5.45	4.45
16	0.036	16	5.46	4.46
17	0.026	17	5.43	4.43
18	0.825	18	5.43	4.43
19	0.226	19	5.75	4.75
20	0.182	20	5.45	4.45
21	0.372	21	5.61	4.61
22	0.180	22	5.46	4.46
23	0.143	23	5.37	4.37
24	0.031	24	5.39	4.39
25	0.408	25	5.41	4.41
26	0.099	26	5.80	4.80
27	0.212	27	5.67	4.67
28	0.097	28	5.49	4.49
29	0.088	29	5.75	4.75
30	0.054	30	5.61	4.61
31	0.045	31	5.67	4.67
32	0.017			

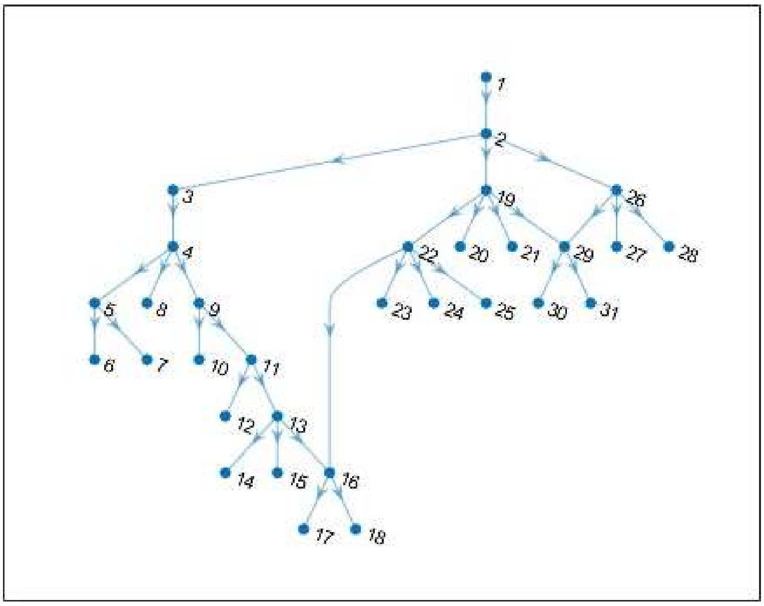

Figure 5. Network generated by MATLAB

For the result, we have checked that the pressure at all the nodes is in the safety range, and the mass flow rate for the branches is correct as well, in the condition that the design demand of the buildings is satisfied.

Then we must recheck the maximum velocity in each branch, according to the UNI-CIG 9165: Gas velocities within pipelines should be low enough to limit the drag of impurities and noise. Maximum velocity should be on the order of:

• 4-5 m/s for pipelines with p ⩽ 0.04 bar

• 10 – 15 m/s for pipelines with pressure ranges between 0.04 and 0.5 bar

• 20 – 25 m/s for pipelines with pressure ranges between 0.05 and 5 bar

Fortunately, all the velocity values shown in table 8 are under the acceptable limit.

Table 8. velocity in branches

Branches	**Rho_act**	**mass flow rate**	**volumetric flow rate**	**A**	**velocity**
List	kg/m3	kg/s	m3/s	m2	m/s
1.00	4.64	2.08	0.45	0.071	6.36
2.00	4.58	0.85	0.19	0.031	5.93
3.00	4.51	0.85	0.19	0.031	6.02
4.00	4.34	0.16	0.04	0.005	7.43
5.00	4.41	0.33	0.07	0.012	6.05
6.00	4.28	0.12	0.03	0.005	5.68
7.00	4.27	0.21	0.05	0.008	6.14
8.00	4.44	0.36	0.08	0.018	4.63
9.00	4.26	0.11	0.03	0.003	7.92
10.00	4.37	0.25	0.06	0.018	3.25
11.00	4.29	0.10	0.02	0.005	4.78
12.00	4.32	0.15	0.03	0.012	2.80
13.00	4.26	0.05	0.01	0.003	3.33
14.00	4.27	0.06	0.01	0.005	2.66
15.00	4.27	0.04	0.01	0.005	2.05
16.00	4.23	0.04	0.01	0.005	1.69
17.00	4.23	0.03	0.01	0.003	1.85
18.00	4.54	0.83	0.18	0.031	5.79
19.00	4.36	0.23	0.05	0.005	10.33
20.00	4.42	0.18	0.04	0.008	5.25
21.00	4.36	0.37	0.09	0.012	6.96
22.00	4.21	0.18	0.04	0.008	5.44
23.00	4.22	0.14	0.03	0.008	4.32
24.00	4.23	0.03	0.01	0.003	2.21
25.00	4.56	0.41	0.09	0.018	5.06
26.00	4.46	0.10	0.02	0.005	4.42
27.00	4.39	0.21	0.05	0.005	9.61
28.00	4.49	0.10	0.02	0.008	2.75
29.00	4.42	0.09	0.02	0.005	3.97
30.00	4.44	0.05	0.01	0.003	3.67
31.00	4.47	0.05	0.01	0.031	0.32
32.00	4.25	0.02	0.00	0.049	0.08

1) What happens to the branch mass flow rates and the nodal pressure distribution if the consumption of each consumers clusters grows by +25%, 50% and 100%?

Is the network still able to satisfy the customers?

And what if this increase affects only a group of contiguous nodes? (You are free to choose the group of nodes you prefer).

Please show in a graph the results of this analysis and comment on them.

Increasing the consumption by +25%, 50% and 100% means that the supplied mass flow rate of gas in the pipeline would be increased by +25%, 50% and 100% to satisfy the demand finally.

After a simple simulation with some complex number results, we noticed that the originally designed network could not satisfy the customers. So, in this case, to make the MATLAB output a correct result based on the SIMPLE algorithm, we should not only change the 'G_ext' of the nodes at the input but also change some branches' diameter to satisfied with the increased mass flow, in case the possible situation occurring which too much mass flow and too little cross-section of the pipeline.

Table 9 below shows the diameter of the branch changed based on the relative mass flow rate, considering some constraints from max velocity and pressure.

Table 9. diameter changing for three conditions

branch list	Original	+25%	+50%	+100%
B1	DN300		DN300-350	DN300-350
B2	DN200	DN200-250	DN200-250	DN200-300
B3	DN200	DN200-250	DN200-250	DN200-300
B4	DN80			DN80-100
B5	DN125			DN125-150
B6	DN80			DN80-100
B7	DN100		DN100-125	DN100-125
B8	DN150		DN150-200	DN150-200
B9	DN65		DN65-80	DN65-100
B10	DN150		DN150-200	DN150-200
B11	DN80			DN80-100
B12	DN125		DN125-150	DN125-150
B13	DN65			DN65-80
B14	DN80			DN80-100
B15	DN80		DN80-100	DN80-125
B16	DN80			DN80-100
B17	DN65			DN65-80
B18	DN200			DN200-250
B19	DN80	DN80-100	DN80-125	DN80-150
B20	DN100			DN100-125
B21	DN125	DN125-150	DN125-150	DN125-200
B22	DN100		DN100-125	DN100-125

B23	DN100			DN100-125
B24	DN65			DN65-80
B25	DN150			DN150-800
B26	DN80			
B27	DN80		DN80-100	DN80-100
B28	DN100			DN100-125
B29	DN80			DN80-100
B30	DN65			DN65-80
B31	DN200		DN200-250	DN200-250
B32	DN250	DN250-300	DN300-350	DN250-400

From the table, it can be noticed, in the condition of consumption increased by 100%, almost all the branches in the system should be replaced with a larger one, especially the ones that act as main branches for the network.

Then, to see what effect the different increasing customers' consumption would bring on the branch mass flow rate and nodal pressure, we had chosen the third version of diameter branches (+100% consumption) as the template network structure and applied the three kinds of increased mass flow rate (+25%, 50% and 100% consumption) on this network structure. The simulation result is below:

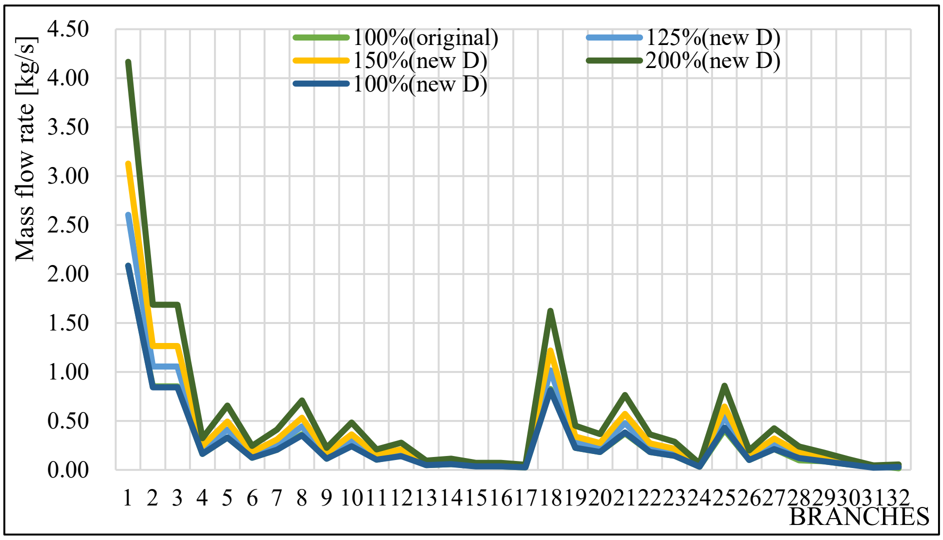

Figure 6. Mass flow rate at different increasing consumption

From this figure, we know that, with the same network structure and branch diameter, the mass flow rate has a similar variation trend in each branch along the pipeline no matter how much the mass flow rate insider is. The only difference is that more consumption leads to more gas flow being needed, which will lead to a larger fluctuation of that along the whole pipeline.

Another thing that should be noticed is that the mass flow rate in B15, B16, and B17 is always little in all conditions. The reason is that these three branches are located at the end of the whole pipeline, and the only element that can affect the mass flow rate in them is the consumption of customers at related nodes.

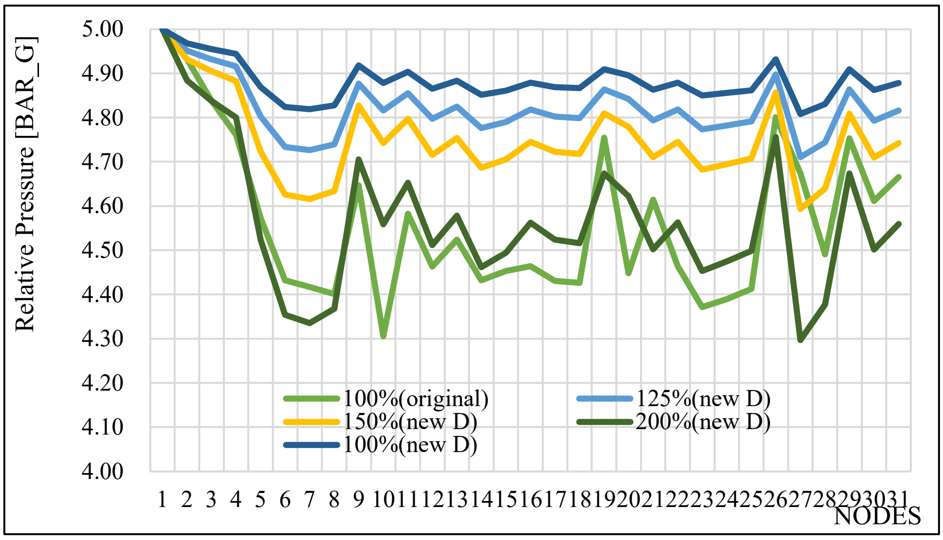

Figure 7. Relative pressure at different increasing consumption

Figure 7 shows the relative pressure distribution along the pipeline in different conditions. At first, we can notice that, in the condition of the same gas consumption, a network structure with a large branch diameter will cause less pressure drop along the pipeline than the one with a stricter branch diameter. In other words, a larger-diameter pipeline structure has a stronger ability to keep the pressure at a stable level in the whole network. Then this figure also demonstrates that, with the same network structure and branch diameter, the pressure distribution has a similar trend at each node along the pipeline no matter how much the gas consumption increased, while more consumption would lead to a larger fluctuation of the relative pressure.

In this part, we make a change on only a group of contiguous nodes (Area 3: N27, N28, N30, N31) increasing the consumption by +25%, 50% and 100%.

For the same reason as before, to make a more accurate and objective comparison regarding the effect of increasing consumption on the gas network. We chose the third version of diameter branches (+100% consumption) as the template network structure and applied the three kinds of increased mass flow rates (+25%, 50% and 100% consumption) at specific nodes on this network structure.

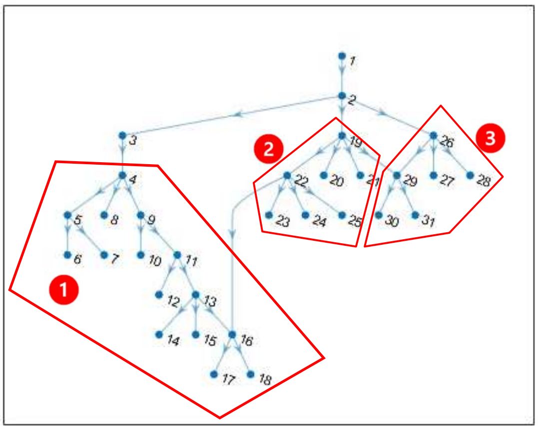

Figure 8. Network generated by MATLAB

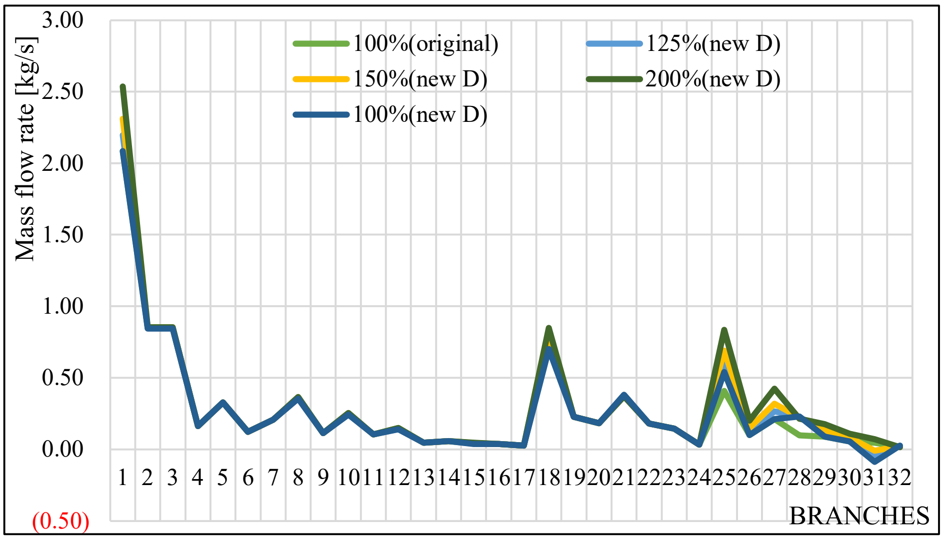

Figure 9. Mass flow rate at different increasing consumption on a group of contiguous nodes

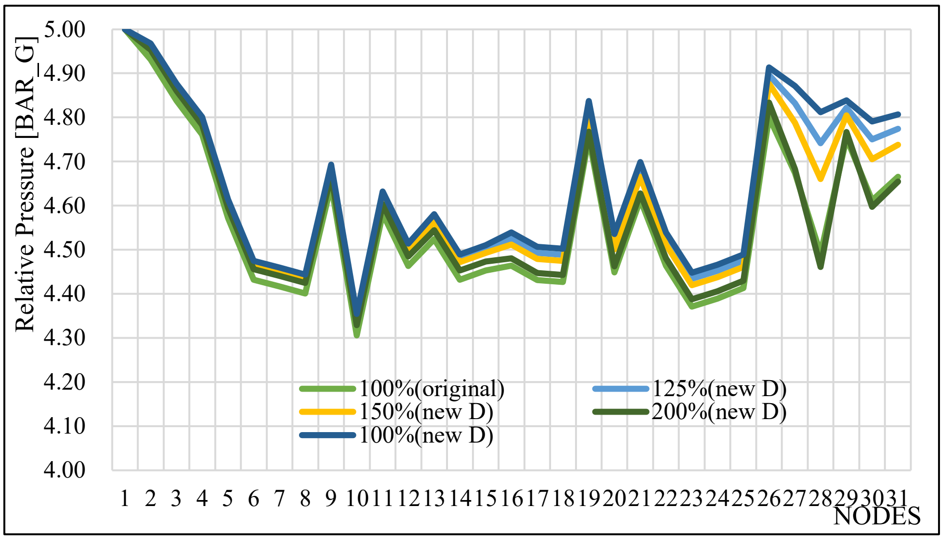

Figure 10. Relative pressure at different increasing consumption on a group of contiguous nodes

We only change the consumption on a group of nodes which are all located in area 3, at the end of the pipeline, so that the branches and nodes that are affected by this increasing consumption become less. As shown in figure 9, the mass flow rate in the branches from B2 to B24 is almost unchanged, while it is changed in B1 (the main branch for the whole network) and B25 to B31 which are all related to area 3. In detail, B25 and B28 is the main branch for area 3, and B31 is the linking branch to connect to area 2 to create a loop. With the consumption increase in N27, N28, N30, and N31, the mass flow rate needed will be increased as well in related branches, which is the reason why B1 and B25 to B31 show a variation in figure 9 under different conditions.

There are two Branches worthy of attention B18 and B31. B18 is the main branch for area 2 that can be connected to area 3 via B31. When the consumption of area 3 increased heavily by +100%, because of the exit of the loop, the gas is not only directly supplied by B25 (the main branch of area 3) but also from B18 and B31 (across area 2), that’s the reason why the mass flow rate of B13 shows an increase in the condition of 200% original consumption.

In this step of the simulation, we chose a relatively larger diameter as the pipeline branch template to satisfy all the conditions. In the case that the user's demand is not very large, there will be a surplus in the gas supply in area 3. In this condition, this part of the surplus gas will flow to area 2 via B31, satisfying part of the user's demand, which will reduce the gas supply requirement of B18. This is the reason why B31 will show a negative value in some conditions in figure 9, that the gas will flow from N29 to N19 rather than from N19 to N29 (the design condition).

2) What happens to the branch mass flow rates and the nodal pressure distribution if one of the loops is opened?

Please compare the case of the full network with the case with one loop opened.

Also, what is the effect of an increase of 25% of all the consumptions in the case of one loop opened?

In this part, we have opened one of the loops by opening Branch 31 (N19-29) and keeping other inputs unchanged at first.

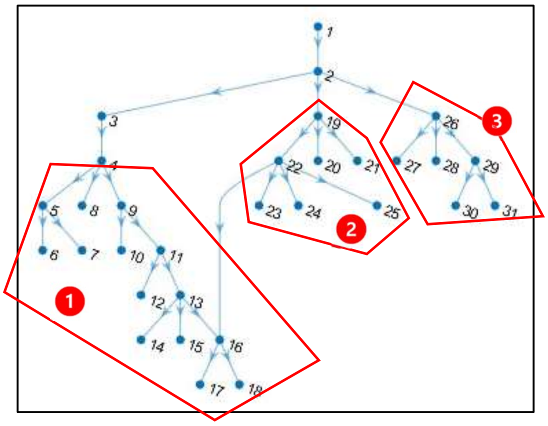

Figure 11. Network generated by MATLAB with one loop opened

The mass flow rate result of each branch from the simulation is shown below, from which we can notice that most of the mass flow rate in branches is not change, while four branches show a little change: B18(N2-N19), B25(N2-N26), B28(N26-N29) and B31. And the difference value roughly equals 0.045 kg/s, which is the mass flow rate of B31 in the original network and it is also the one we opened in this case.

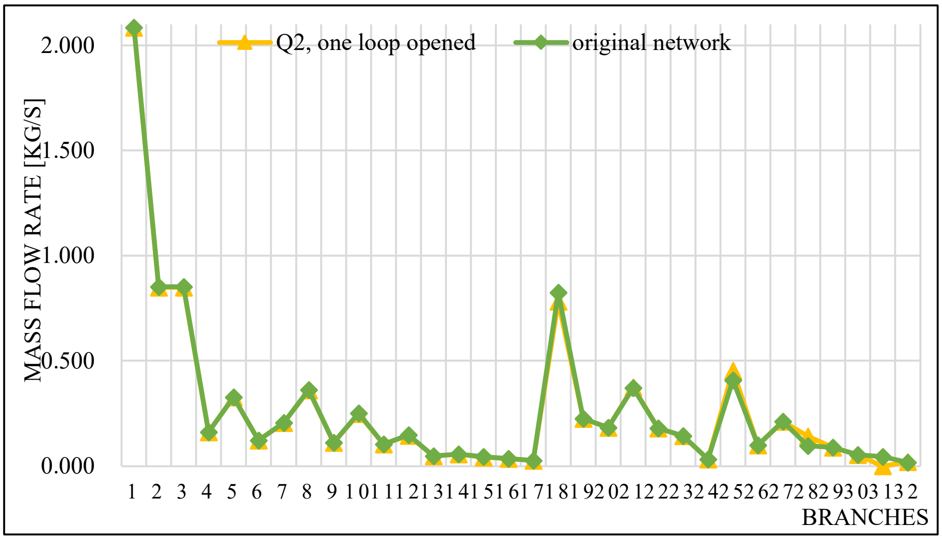

Figure 12. The mass flow rate in the original network and with one loop opened

From the topology of the network (figure 11), we know that B18, B25 and B28 is the main pipe for area 2 and area 3, respectively, and the B31 that opened is a linkage connecting area 2 and area 3. Once this linking line is not work, all the flow that is used to satisfied with the gas demand of area 3 would be carried through B25 and then

B28. While in the original network structure, this gas demand could be satisfied not only by the flow from B25 but also by the flow from area 2 via B31 as a linking pipe. That is the reason why the mass flow rate in B18, B25 and B28 has been changed due to the opened loop. For the B31, it is opened, so no flow would be in it, m31 equals '0'.

Regarding the pressure of the nodes, from the following figure, we know that the most noticeable is the decreasing pressure at N29, N30, and N31, which are the extremity nodes of area 3. Once the loop is opened, all the gas demand in the area3 is supplied via B25 and then B28, which is described before, in this situation, the pressure drop along this pipeline will increase for no loop helping to balance the flow, so that, as the end of area3, N29, N30, N31 are the most affected ones.

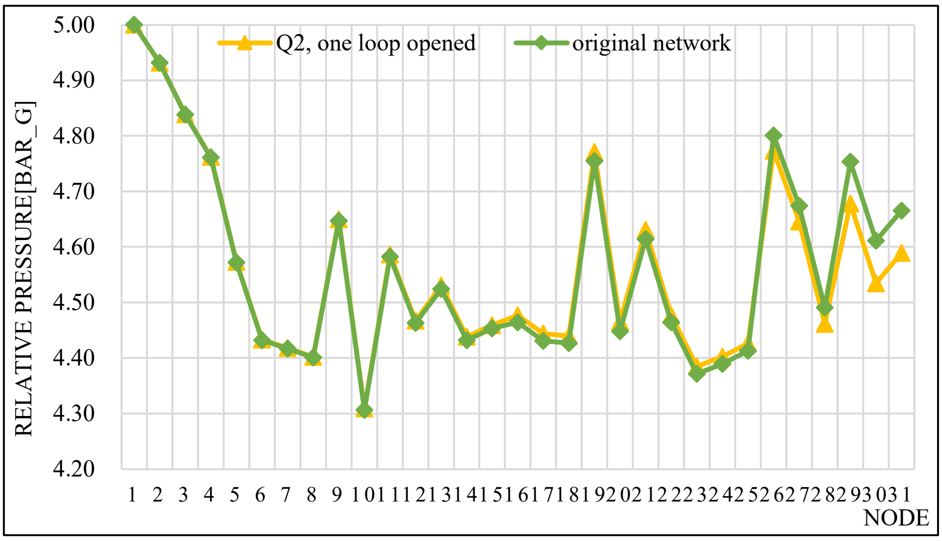

Figure 13. Relative pressure in the original network and with one loop opened

Then, we are going to increase the consumption by 25% on the loop-opened network. In this case, we have to change the parameter 'Gguess' in the branch input and the 'G_ext' in the node's input. But unfortunately, the diameter of the pipeline cannot be satisfied with the gas demand in this situation, so we will change some pipes' diameters to meet the increasing consumption under the constraints of max velocity.

The diameters of the Branches changed:

B2 – from DN200 to DN250, one of the main branches for area1

B3 – from DN200 to DN250, one of the main branches for area1

B8 – from DN150 to DN200, one of the main branches for area1

B19 – from DN80 to DN100

B21 – from DN125 to DN150, one of the main branches for area2

B32 – from DN250 to DN300, another branch creates a loop.

We have changed the diameter of some main branches in a different area to cope with the increased consumption. The B19 that is connected to a building has been changed too because the increased mass flow rate increases the velocity in this branch which will be out of the maximum limit.

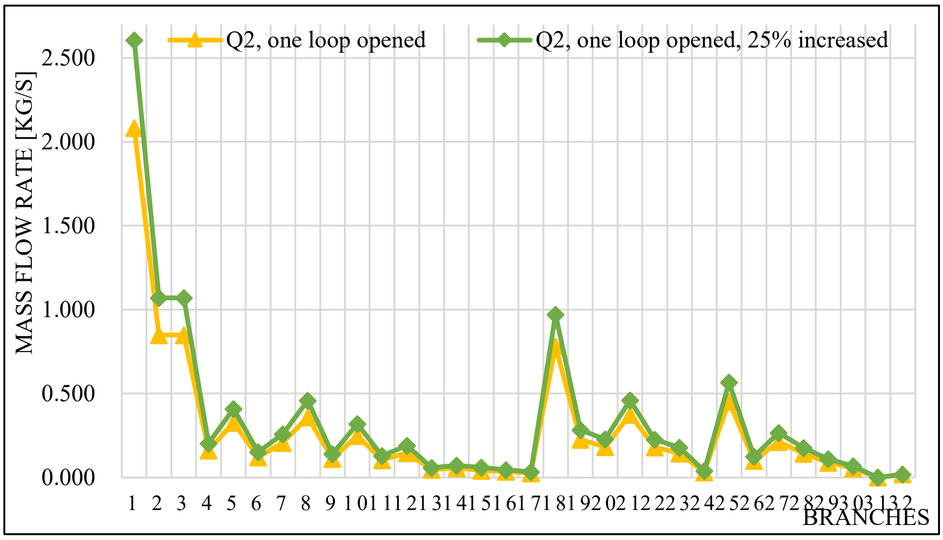

Figure 14. The mass flow rate in the network with one loop opened and with an increasing 25%

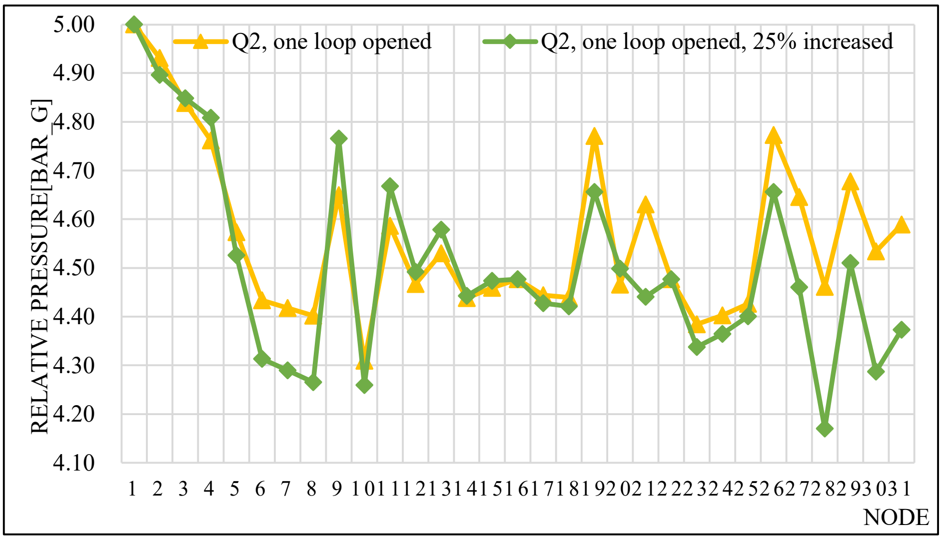

Figure 15. Relative pressure in the network with one loop opened and with an increasing 25%

From figure 14, we can notice that the mass flow rate in all branches shows an increase due to more than 25% gas consumption, especially the one in the main branches for each area. Regarding the pressure of the nodes, the figure displays more fluctuations, at the condition with more than 25% gas consumption. It may be because the increased mass flow rate causes an increase in the pressure to unbalance furtherly, in the condition that one loop has been opened. Meanwhile, most of the points with large variations in pressure are usually located at the end of the network.

To conclude, when a loop of the network is opened, the mass flow rate in the branches that used to create this loop will be zero, and to compensate for this disappeared flow and supply, the flow rate in other branches will increase relative to satisfy the final demand. Moreover, the loop in the gas network also plays a role that can help to balance the pressure in the pipeline and reduce the pressure drop for some nodes to some extent.

3) What happens to the branch mass flow rates and the nodal pressure distribution if the gas feeding the network is a mixture of your chosen natural gas and 20% hydrogen?

Is the quality of the distributed gas still in compliance with the Italian gas quality regulation?

Considering satisfying the same thermal energy request at each cluster of users, how do the volumetric flow rates change at the consumption nodes and along the branches?

What about the nodal distribution? Please compare this situation with the case with no hydrogen.

The natural gas used in this project is from Gas Algerino, table 10 shows the parameters of this natural gas. The mixture of hydrogen and natural gas alters the composition and properties of the gas flowing through the system, the property of the new synthesized gas is shown in the following table as well.

Table 10. Gas Properties

Composition	Unit	Gas Algerino	Mixture Gas @ 20% H2
Methane	%MOLE	85.87	68.698
Ethane	%MOLE	9.48	7.585
Propane	%MOLE	1.342	1.073
Nitrogen	%MOLE	1.22	0.972
Carbon dioxide	%MOLE	2.09	1.672
Hydrogen	%MOLE	0	20
Molar weight	[Kg/kmol]	18.59	15.28
High heating value	[kWh/Sm^3]	11.160	9.5764
High heating value	[MJ/Sm^3]	40.176	34.4750
Low heating value	[kWh/Sm^3]	10.091	8.6214
Density	[kg/Sm^3]	0.78836	0.6478
Wobbe index	[MJ/Sm^3]	50.0904	47.4086
Relative density		0.64334	0.5280

From the table, we can compare with the Italian Gas Quality Regulations, which require:

34.95<High Heating Value<45.28,

47.31<Wobbe Index<52.33,

0.555<Relative Density<0.7.

According to the regulations, the new gas mixture with 20% hydrogen does not comply with the regulation.

But, if we ignore the requirements of the regulations, let the new gas with 20% hydrogen be added to the gas system. Hydrogen has different properties than natural gas, such as a lower density and different combustion characteristics, which can impact the mass flow rates and nodal pressure distribution throughout the network. The volume fractions in table 11 are derived from the densities, which are inversely proportional to the volume fraction. Due to the lower density of hydrogen, the volume flow rate of the mixed gas is slightly greater than that of the natural gas.

Table 11. Comparison with the original gas and the mixture gas with 20% H_2

Branches List	Nodes Linked	original gas		new mixture gas	
		mass flow rate	volumetric flow rate	mass flow rate	volumetric flow rate
		kg/s	m3/s	kg/s	m3/s
4	N4-N8	0.162	0.037	0.155	0.043
6	N5-N6	0.122	0.029	0.117	0.033
7	N5-N7	0.206	0.048	0.198	0.056
9	N9-N10	0.112	0.026	0.108	0.031
11	N11-N12	0.103	0.024	0.099	0.028
13	N13-N14	0.047	0.011	0.045	0.013
14	N13-N15	0.057	0.013	0.055	0.016
16	N16-N17	0.036	0.009	0.034	0.010
17	N16-N18	0.026	0.006	0.025	0.007
19	N19-N20	0.226	0.052	0.217	0.060
20	N19-N21	0.182	0.041	0.175	0.048
22	N22-N23	0.180	0.043	0.173	0.049
23	N22-N24	0.143	0.034	0.138	0.039
24	N22-N25	0.031	0.007	0.030	0.009
26	N26-N27	0.099	0.022	0.096	0.026
27	N26-N28	0.212	0.048	0.204	0.056
29	N29-N30	0.088	0.020	0.085	0.023
30	N29-N31	0.054	0.012	0.052	0.014

The node highlighted in yellow is the consumption node that is considered coincident with the secondary reduction plants in which all the downstream consumptions are clustered.

Then, to make the new mixture gas that can be injected into the network, the percentage of hydrogen should be reduced from 20% to 10%, and finally, we recheck its properties:

34.95<High Heating Value = 37.36 <45.28,

47.31<Wobbe Index = 48.75 <52.33,

0.555<Relative Density = 0.585 <0.7.

At this time, the related parameters are satisfied with the regulated range, so the new mixture of gas with 10% hydrogen can be injected into the gas network now.

After the simulation, we got the result of the new mixture gas with 10% H_2 combined with as follows, and the comparison of the original gas and new mixture gas is also shown in the following figure:

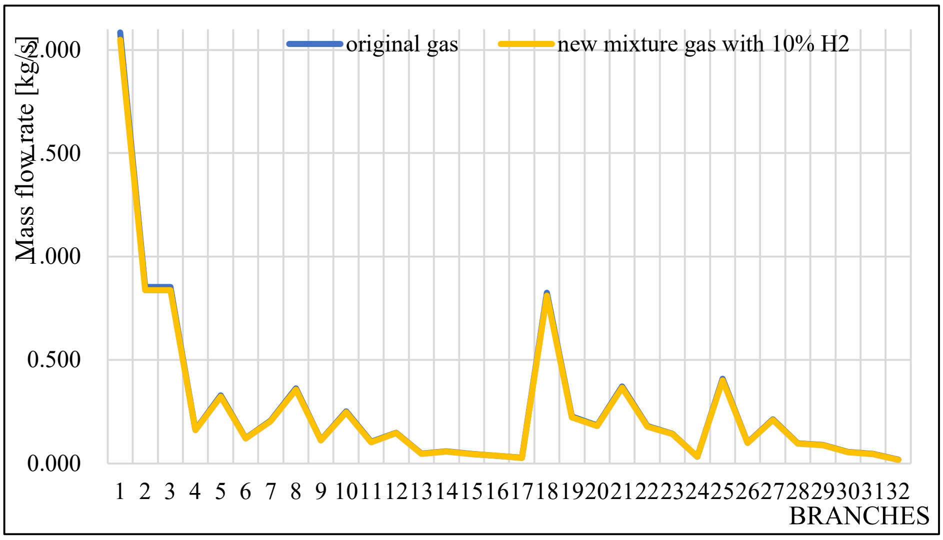

Figure 16. The mass flow rate in the network for original gas and new mixture gas with 10%H2

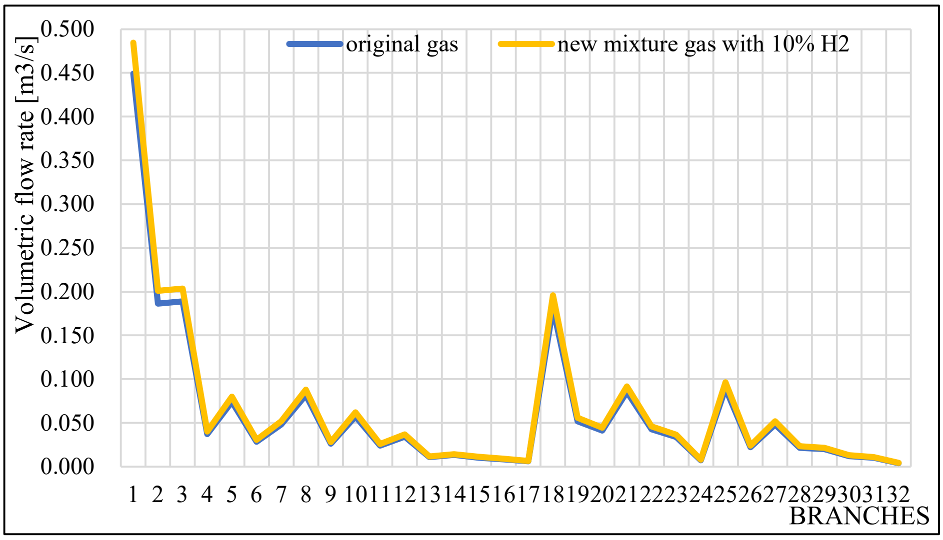

Figure 17. The volumetric flow rate in the network for original gas and new mixture gas with 10%H2

From figure 16, we can know that when the heat demand condition (Φ_d) remains unchanged, the mass flow rate of the new mixture gas (yellow line) is a little less than the original gas (blue line). But the difference is very small, and hard to distinguish. It is because the mass flow rate is calculated based on the following equation.

$$\dot{Q}\left[\frac{Sm^3}{h}\right] = \frac{\Phi_d[kWh]}{\eta_{boiler} \cdot LHV\left[\frac{kWh}{Sm^3}\right]}$$

$$\dot{m}\left[\frac{kg}{h}\right] = \dot{Q}\left[\frac{Sm^3}{h}\right] * \rho_n$$

Where ρ_n is the standard gas density.

And, in this condition, the LHV and standard gas density of the original gas and new mixture gas are roughly similar for they both are in a regulated range which is not very wide. So, the final calculated mass flow rate needed is roughly similar, with the total mass flow rate equal to 2.049 [kg/s] in B1 for the new mixture gas and this value equals 2.084 [kg/s] for the original gas.

Regarding the volumetric flow rates change, it is different from the mass flow rate discussed above. The mass flow rate of the new mixture gas (yellow line) is a little larger than the original gas (blue line). The reason is that the volumetric flow rate is obtained based on the actual density at a specific pressure and temperature. It can be calculated from the mass flow rate with the following equation:

$$Q_{actual}\left[\frac{m^3}{s}\right] = \frac{\dot{m}\left[\frac{kg}{s}\right]}{\rho_{actual}\left[\frac{kg}{m^3}\right]}$$

$$\frac{P}{\rho_{actu}} = z\frac{R_0}{MM}T$$

From this equation, we can know that the actual density is proportional to the pressure and Molar mass. In the last past, we have already calculated the molar mass of the new mixture gas with 10% H2 (16.93 [Kg/kmol]), while the one of the original gas is 18.59 [Kg/kmol]. In the condition that means the pressure of branches inlet and outlet are similar which is shown in the following figure, the value of the actual density of the new mixture gas is lower than that of the original one at each specific temperature. So, the volumetric flow rate that is inversely proportional to the actual density of the new mixture gas will be larger than the original gas.

In terms of the total pipeline, in those branches that carry less gas, the difference in the volumetric flow rate of original gas and new mixture gas is less. In other words, in the same condition of heat demand, the more gas the branch carried, the larger the volumetric flow rate would be in the condition of the new mixture gas concerning the condition of the original gas.

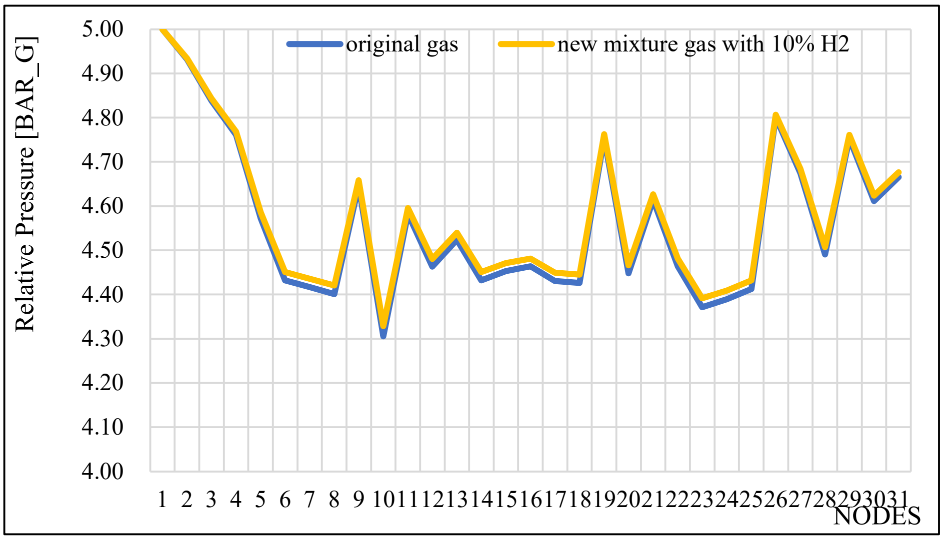

Figure 18. Relative pressure in the network for original gas and new mixture gas with 10%H2

Figure 18 shows the distribution of relative pressure at each node along the pipeline. We can notice that the overall trend is similar for both the original gas and the new mixture gas, while the pressure drop of the new mixture gas along the pipeline is a little lower than the original one. We suppose the reason is that the total mass flow rate of the new mixture gas needed to satisfy the demand is a little less than that of the original gas, which makes the pressure drop reduced to some extent. Moreover, hydrogen has some different properties than the original gas, such as a lower density and different combustion characteristics, which can also impact nodal pressure distribution throughout the network.