

Online Supplement to *Convex Relaxations for Gas Expansion Planning*

Conrado Borraz-Sánchez, Russell Bent, Scott Backhaus,
Hassan Hijazi, and Pascal Van Hentenryck

This document contains supplementary material related to the data sets used to conduct the computational experiments described in the paper.

1 The Benchmarks

1.1 The Belgian Network

Table 1 shows the list of test instances based on the Belgian network depicted in Figure 1. The table shows, for each benchmark, the number of nodes, sources, terminals, base pipelines, and compressor stations, as well as the number of new components (pipelines and compressors) that can potentially be added to the network topology. Note that benchmark A in Table 1 is the real Belgium gas transmission network, and Table 2 shows the node characteristics for this 20-node, 24-pipeline, 3-compressor network. The reader is referred to the appendix of (De Wolf and Smeers 2000) for further details on this network.

Instances $A_1 - A_3$ capture various possible expansions to the Belgian base network. Figure 2 and Tables 3 and 4 depict the location of the potential expansion plans and their associated data. The network expansion plans were designed for the Belgian gas network in order to capture events such as increase of the number of nominations and forecasting demand at the city gates, as well as excessive stress of the available supplies at the sources.

Instances $B_1 - B_4$ are based on the “optimization from scratch” benchmarks from (De Wolf and Smeers 2000) and (Babonneau et al. 2012), where an increasing weighting factor $\alpha = \{1, 1.6, 5, \text{ and } 6\}$, respectively, was used on the investment cost function. In these papers, the authors use the Belgian gas network for a variation of the GTNEP problem that minimizes a combination of operating and expansion costs (the combinations are weighted by α). These benchmarks specify minimum and maximum production levels (see Table 5). Since the GTNEP assumes known gas nomination and production profiles, we computed load and

Ref	Network configuration						
	\mathcal{N}	\mathcal{I}	\mathcal{D}	Base		New	
				\mathcal{P}_e	\mathcal{C}_e	\mathcal{P}_n	\mathcal{C}_n
A	20	6	9	24	3	0	0
A_1	22	6	9	24	3	4	2
A_2	25	6	9	24	3	7	4
A_3	29	6	9	24	3	12	5
B_1	20	6	9	0	0	135	12
B_2	20	6	9	0	0	135	12
B_3	20	6	9	0	0	135	12
B_4	20	6	9	0	0	135	12

Table 1: Test Instances Based on the Belgian Network.

compression profiles based on optimal pressures provided in (Babonneau et al. 2012). Our instances also employ the same cost function as in (Babonneau et al. 2012) to compute the associated costs for building new pipelines, i.e.,

$$L_{ij} (1.04081^{-6} D_{ij}^{2.5} + 11.2155)$$

where D_{ij} and L_{ij} are the diameter and length of pipeline (i, j) , respectively.

Babonneau et al. (2012) assumed continuous diameter choices. However, we used discrete diameter values corresponding to the solution provided in (De Wolf and Smeers 2000) and in Table 4 of (Babonneau et al. 2012). For completeness, the diameter choices are described in Table 6. Note that the exclusive-set constraint is slightly different for these cases due to the existence of pre-defined parallel pipes. Within in each row of Table 6, the solution must contain one and only diameter choice, and each set of parallel pipes must choose diameters from the same column of Table 6.

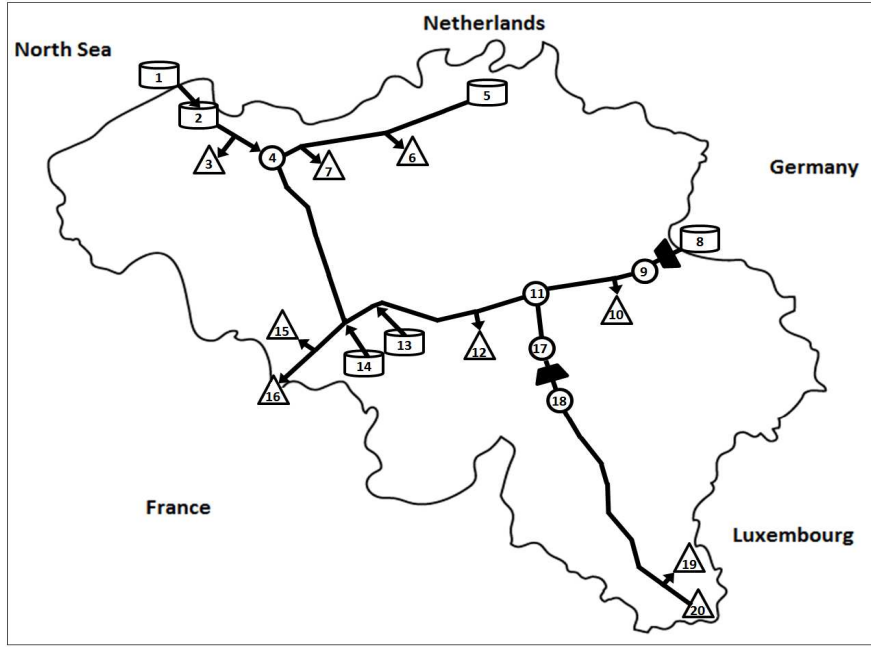


Figure 1: The Belgian Gas Network Base Configuration (case A).

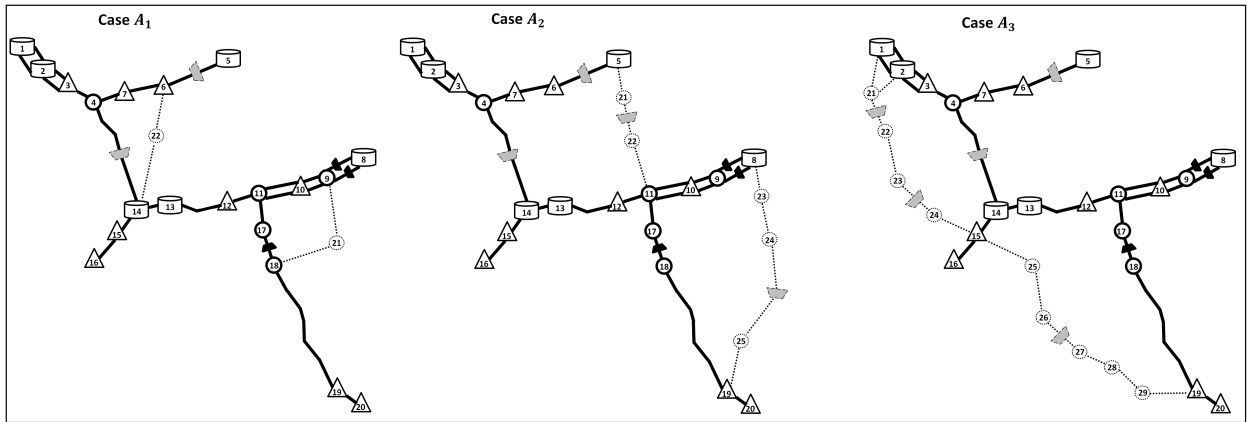


Figure 2: The Belgian Gas Network Expansion Plans (Instances A_1 – A_3).

Node (Loc.)	Type ^(*)	(Loads)			(Pressure)	
		\underline{L}	\overline{L}	L	\underline{P}	\overline{P}
1 (Zeebrugge)	\mathcal{I}	8.87	11.594	10.911288	0	77
2 (Dudzele)	\mathcal{I}	0	8.4	8.4	0	77
3 (Brugge)	\mathcal{D}	$-\infty$	-3.918	-3.918	30	80
4 (Zomergem)		0	0	0	0	80
5 (Loenhout)	\mathcal{I}	0	4.8	2.814712	0	77
6 (Antwerp)	\mathcal{D}	$-\infty$	-4.034	-4.034	30	80
7 (Ghent)	\mathcal{D}	$-\infty$	-5.256	-5.256	30	80
8 (Voeren)	\mathcal{I}	20.34	22.01	22.012	50	66.2
9 (Berneau)		0	0	0	0	66.2 [†]
10 (Liège)	\mathcal{D}	$-\infty$	-6.365	-6.365	30	66.2
11 (Warnand)		0	0	0	0	66.2
12 (Namur)	\mathcal{D}	$-\infty$	-2.12	-2.12	0	66.2
13 (Anderlues)	\mathcal{I}	0	1.2	1.2	0	66.2
14 (Péronnes)	\mathcal{I}	0	0.96	0.96	0	66.2
15 (Mons)	\mathcal{D}	$-\infty$	-6.848	-6.848	0	66.2
16 (Blaregnies)	\mathcal{D}	$-\infty$	-15.616	-15.616	50	66.2
17 (Wanze)		0	0	0	0	66.2
18 (Sinsin)		0	0	0	0	63
19 (Arlon)	\mathcal{D}	$-\infty$	-0.222	-0.222	0	66.2
20 (Pétange)	\mathcal{D}	$-\infty$	-1.919	-1.919	25	66.2

Table 2: The Belgian Gas Network Data from (De Wolf and Smeers 2000). This data is used for the A Problems. †- On Problems A1, A2, and A3, the pressure bounds are $[0, 59.851968]$, $[0, 59]$, and $[0, 59.85]$ respectively.

Node	Town	Lat.	Long.	$\underline{P}^{(*)}$	$\overline{P}^{(*)}$
<i>Instance A₁</i>					
21	Bois	50.400676	5.855991	14	66
22	Koninklijke	50.806672	4.481877	14	66
<i>Instance A₂</i>					
21	Heist	51.095651	4.744616	20	70
22	Zoutleeuw	50.858734	5.115404	20	70
23	Beaufays	50.552195	5.670182	20	70
24	Gouvy	50.231757	5.966813	20	70
25	Ettelbruck	49.861370	6.073930	20	70
<i>Instance A₃</i>					
21	Jabbeke	51.204699	3.086440	14	66
22	Torhout	51.072867	3.118026	14	66
23	Kortrijk	50.790711	3.230636	14	66
24	Bois-de-Barry	50.580151	3.521773	14	66
25	Lobbes	50.353208	4.263261	20	70
26	Senzeille	50.124840	4.433550	20	70
27	Gedinne	49.980230	4.851030	20	70
28	Chiny	49.806832	5.274004	20	70
29	Pigneule	49.735878	5.471758	20	70

Table 3: Locations of Nodes of the Expansion Plans for the Belgian Gas Network. These nodes do not have injections.

Node1	Node2	w	c
<i>Instance A₁</i>			
9	21	0.929	67.19
21	18	0.808	77.26
6	22	0.785	79.50
22	14	0.766	81.44
<i>Instance A₂</i>			
5	21	1.052	59.29
21	21*	Compressor	1500.0
22	11	0.967	64.52
8	23	1.933	32.28
23	24	0.876	71.18
24	24*	Compressor	1500.0
25	19	1.339	46.59
21*	22	0.980	63.65
24*	25	0.866	72.08
<i>Instance A₃</i>			
1	21	2.257	27.65
2	21	4.546	13.73
21	21*	Compressor	1500.0
22	23	1.121	55.66
23	23*	Compressor	1500.0
24	15	1.073	58.14
15	25	1.483	42.09
25	26	1.289	48.40
26	26*	Compressor	1500.0
27	28	1.010	61.79
28	29	2.232	27.96
29	19	1.423	42.09
21*	22	2.448	25.50
23*	24	1.165	53.56
26*	27	1.071	58.28

* Denotes introduced dummy node for 0 length compressor arcs

Table 4: Locations of Pipes of the Expansion Plans for the Belgian Gas Network.

Node	Load (L) profiles (MMscf)			
	B_1	B_2	B_3	B_4
1	9.5883	9.8225	9.8218	9.7205
2	8.1833	8.3447	8.1340	8.3628
3	-3.9180	-3.9180	-3.9180	-3.9180
4	0.0000	0.0000	0.0000	0.0000
5	4.0315	4.0432	4.0383	4.0364
6	-4.0315	-4.0432	-4.0383	-4.0364
7	-5.2413	-5.2644	-5.2562	-5.2644
8	22.012	22.0120	22.0120	22.0120
9	0.0000	0.0000	0.0000	0.0000
10	-6.4744	-6.4951	-6.3970	-6.3816
11	0.0000	0.0000	0.0000	0.0000
12	-2.1929	-2.1191	-2.1162	-2.0984
13	1.2162	1.3225	1.0802	1.1591
14	0.9840	0.6164	1.0776	1.0235
15	-6.4056	-6.5885	-6.8366	-6.8857
16	-15.6119	-15.5904	-15.4616	-15.5899
17	0.0000	0.0000	0.0000	0.0000
18	0.0000	0.0000	0.0000	0.0000
19	-0.2059	-0.2312	-0.2269	-0.2164
20	-1.9337	-1.9112	-1.9131	-1.9236

Table 5: The Load Profiles Computed from Optimal Pressures Provided in (Babonneau et al. 2012). All compression ratios were derived as 1.0.

Pipe	D_1	D_2	D_3	D_4	D_5
(1,2) A	890.0	650.3	610.8	524.7	512.1
(1,2) B	890.0	650.3	610.8	524.7	512.1
(2,3) A	890.0	834.7	784.0	673.5	657.3
(2,3) B	890.0	834.7	784.0	673.5	657.3
(3,4)	890.0	998.9	938.3	806.0	786.7
(5,6)	590.1	604.3	567.6	487.6	475.9
(6,7)	590.1	0	X	X	X
(7,4)	590.1	671.7	630.9	542.0	529.0
(4,14)	890.0	829.9	779.5	669.7	653.6
(8,9) A	890.0	902.8	848.0	728.4	711.0
(8,9) B	395.5	902.8	848.0	728.4	711.0
(9,10) A	890.0	902.8	848.0	728.4	710.9
(9,10) B	395.5	902.8	848.0	728.4	711.0
(10,11) A	890.0	787.6	739.8	635.5	620.1
(10,11) B	395.5	787.6	739.8	635.5	620.4
(11,12)	890.0	979.8	920.3	790.6	771.6
(12,13)	890.0	915.1	859.6	738.4	720.7
(13,14)	890.0	952.6	894.7	768.6	750.1
(14,15)	890.0	1201.0	1128.0	969.0	945.8
(15,16)	890.0	1038.4	975.3	837.9	817.7
(11,17)	395.5	469.0	440.5	378.4	369.3
(17,18)	315.5	469.0	440.5	378.4	369.3
(18,19)	315.5	469.0	440.5	378.4	369.3
(19,20)	315.5	448.9	421.7	362.2	353.5

Table 6: Pipe diameter choices from Table 4 of (Babonneau et al. 2012)

1.2 Larger Networks

Table 7 describes the main data points for the larger benchmarks. Instance D is a real-life network case whose data is restricted for confidentiality reasons and we are not allowed to disclose its map or load profile. Instances E , F , and G correspond to a collection of technical, real-world gas networks taken from GasLib (2014), a library of gas network instances (Pfetsch et al. 2015, Humpola et al. 2015), with data provided by the gas transport company *Open Grid Europe GmbH* as a part of the BMWi project “Technical Capacities of Gas Networks”. The GasLib library, besides including the network configurations with their underlying coordinates, also specifies load profile scenarios. We considered scenario id=“nomination_1” for instances E (GasLib-40) and F (GasLib-135), and scenario id=“nomination_cold_5” for instance G (GasLib-582).

Ref.	Network configuration					
	$ \mathcal{N} $	$ \mathcal{I} $	$ \mathcal{D} $	Base		New
				$ \mathcal{P}_e $	$ \mathcal{C}_e $	$ \mathcal{P}_n $
D	60	2	24	55	4	55
E	40	3	29	39	6	39
F	135	6	99	141	29	141
G	582	31	129	609	5	278

Table 7: Larger Instances of Gas Networks.

2 Characteristics of the Models

Tables 8 and 9 show the sizes of the underlying models in terms of the number of binary and continuous variables and the number of linear and quadratic constraints for each instance.

Bench.	MINLP				PLA-MIP				MISOCP			
	BV	CV	LC	QC	BV	CV	LC	QC	BV	CV	LC	QC
<i>A</i>	54	49	254	96	1494	1837	3931	0	54	73	398	24
<i>A</i> ₁	70	59	320	112	1750	2151	4605	0	66	91	488	28
<i>A</i> ₂	85	69	389	124	1945	2391	5120	0	78	107	575	31
<i>A</i> ₃	103	80	463	144	2263	2776	5954	0	91	128	679	36
<i>B</i> _{1,2,3,4}	354	1154	464	357	7314	8737	19067	0	238	373	1850	116

Table 8: The Sizes of the Mathematical models for Belgian Network Instances. (BV: Binary variables, CV: Continuous variables, LC: Linear constraints, QC: Quadratic constraints).

Ref.	MINLP				PLA-MIP				MISOCP			
	BV	CV	LC	QC	BV	CV	LC	QC	BV	CV	LC	QC
<i>D</i>	283	174	1093	440	6883	8330	18018	0	228	339	1753	110
<i>E</i>	207	124	792	312	4887	5920	12796	0	168	241	1260	78
<i>F</i>	763	446	2886	1128	17683	21430	46304	0	622	869	4578	282
<i>G</i>	2101	1469	8058	2256	35941	44433	92848	0	1823	2311	11442	564

Table 9: Size of the Mathematical Models: BV: Binary variables, CV: Continuous variables, LC: Linear constraints, QC: Quadratic constraints.

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