PSIG 1014

Optimizing gas transport with the route planner

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This paper was prepared for presentation at the PSIG Annual Meeting held in Bonita Springs, Florida 11May – 14 May 2010.

ABSTRACT

In this paper we present the first experiences with a prototype model-based decision support tool known as the “route planner for gas transport”. The route planner is an on-line tool that advises dispatchers on how to minimise operational costs while maintaining security of supply. The tool consists of a reduced network model of the Dutch gas transport network that can be loaded with actual network configuration and flow forecasts for upcoming 24 hours. The output is the cost optimal use of compression, gas blending including nitrogen ballasting and supply flexibility for network balancing. In short, the route planner finds the most cost effective route through the transport network to meet end-user demand for the upcoming day.

The basic concept was presented at the PSIG 2009 [1], with the focus on demonstrating the “apparent intelligence” of the optimizer core when facing decision dilemma's. This study was for a subsection of the network only. Since then practical experiences have been gained with the complete prototype system and for the entire network, namely:

- The prototype has demonstrated to be able to maintain its "apparent intelligence" even for a five times more complex network, creating plans with a similar feel to them as those made by dispatchers.

- Dedicated routines for the automatic calibration of the reduced network models were found to be essential for operating the tool in a real life environment and for gaining trust in its advice.

- Modelling the blending stations and nitrogen ballasting during the low flow situations in summer proved to be more challenging then the modelling of the compressor stations during the winter.

- The tests demonstrated that the main task of the route planner is to provide strategic advice on the use of stations, rather then providing detailed set points for a particular station. This illustrates once more that the route planner is intended to work intimately together with a simulator, rather then replacing it.

In this paper we will briefly re-introduce the concept, present the key findings of the replay tests. We will also introduce a potential spin-off application that might be of interest for gas transport companies in general. In principle it is rather straight forward for the route planner to rerun past and future cases with various levels of safety margins, thus creating insight in the cost impact of the various operational margins.

MOTIVATION

With the unbundling of the integrated company Gasunie in 2005 in the trading company GasTerra and the transport company Gasunie. The operator of the Gasunie network is Gas Transport Services (GTS). With the unbundling the day-to-day gas dispatching process has become considerably more complex. The network is now open to a much larger number of shippers and gas brought into the network can be traded on the TTF spot market. In the mean time indigenous supply flexibility has decreased, new pipelines, LNG terminals, storages come on-line and energy prices have doubled. The challenge for the transport company Gasunie is to reduce costs for compression, gas quality conversion and gas supply flexibility in this new market environment in order to maintain profit margins, whilst maintaining security of supply.

Gasunie Engineering & Technology, since July 2009 part of KEMA, is investigating the use of an on-line model-based decision support tool for gas dispatching, also known as the "route planner for gas transport". The task of the route planner is to provide real time information on the most cost effective manner to operate the gas transport network in the upcoming

24 hours. The name "route planner" was chosen for two reasons: a) the purpose of the tool is to find optimal routes for gas through the transport network and b) to provide a useful metaphor for establishing the desired functionalities of the tool.

DUTCH GAS TRANSPORT NETWORK

The route planner has to operate in the environment of the Dutch gas transport system. The key technical features are [2,3]:

- 3750 miles [6000 km] of high pressure transport pipeline and 3750 miles of medium pressure regional distribution pipeline, summing up a total of 7500 miles [12.000 km].
- 3390 BCF [96 BCM] gas transported annually.
- 15 compressor stations, 35 blending stations, (4 including Nitrogen), 43 production entries, 16 border points and 1180 delivery points.

Key economic figures Gasunie (2007):

- 1.3 billion euro annual revenue, 435 million euro profit after taxes.
- Annual use of 6.7 BCF [190 MCM] gas and 150 GWh electricity.

What sets the Dutch system apart from most other transport systems is the wide range of gas qualities that need to be dealt with. We distinguish the gas qualities: H^+ from Norway, H, H^- and L from the small Dutch fields and G from the large Groningen field. Calorific values range from 44 MJ/m^3 (H^+) to 35 MJ/m^3 (G) and blending stations allow for downward quality conversion (i.e. H to L, L to G, etc). H-gas is used for indigenous power generation and industrial processes and is exported to the UK, Belgium and Italy (via German network). L-gas with a wide quality band is supplied to the Belgium and German residential/commercial markets and G-gas with a narrow quality band is used for the Dutch residential/commercial market.

Both L-and G exits traditionally show large seasonal demand swings and can be very unpredictable, especially during flank periods of the heating season. The H-gas system is also becoming more and more dynamic due to increasing trading movements with the neighboring countries. This combined with the interconnection of the various gas quality networks via blending stations creates a dynamic interplay that dispatchers and the route planner must deal with.

ECONOMICS

The goal of the route planner tool is to eventually create real economic value for the end-user on a day-to-day basis. It can do so by:

- Minimizing daily operational costs for compressor fuel, nitrogen ballasting and use of flexible entries (fields and storages) for network balancing.
- Assisting dispatchers in avoiding network operation outside of contractual limits.
- Quantizing the up to now unclear costs of the operational margins used to ensure security of supply during unexpected events.
- Streamlining the daily planning processes and allowing dispatchers to focus more on their core activities.

The main target set for the route planner is to shave at least 5% of the total operational costs. This value is derived from previous experiences with decision support tools and is considered to be not unrealistic by the Gasunie experts. Given these savings, the total costs for the implementation of the route planner tool will be earned back in ~1 year. The other economic benefits can then be considered as a bonus.

OPTIMIZER ENGINE DESIGN

In order to have the full creative freedom during the early stages of development we chose to work with the AIMMS rapid prototyping platform for optimizers using a CPLEX solver [4]. Simplified models of the gas transport network were constructed in a similar manner to those in our simulation tools MCA and GUS [5,6]. Figure 1 illustrates the manner in which the simplified networks are constructed, in this case a blending station:

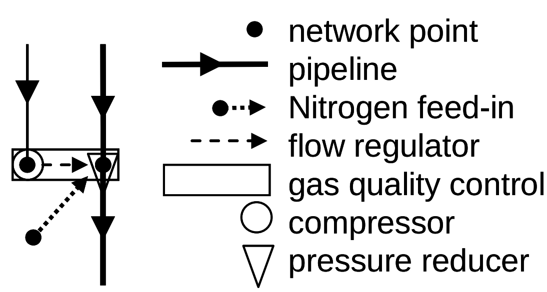

Figure 1 - example of the network blocks used in the route planner (blending station).

Network points connect pipelines and may contain a gas entry or an exit, compression, pressure reduction or may be part of a blending station. By assigning multiple properties to a single network point the total number of network points can be limited, hence minimizing data streams and calculation time. Flow through the (generalized) pipelines is allowed to be bi-directional and the intrinsic gas buffer of the pipelines (line-pack) is included in the flow balance.

VARIABLES AND PARAMETERS

The main output variables to be determined by the solver engine are:

- Pressure per node.
- Compression and pressure reduction per station.
- Transport per pipeline, including line pack.
- Entry and exit flows.
- Gas blending and nitrogen flows.

The main input parameters are:

- Pipeline volume and flow-pressure drop characteristics.
- Predicted entry and exit flows.
- Compressor station efficiency and range.
- Blending stations quality bandwidths and Nitrogen availability.
- Real time Nitrogen and fuel prices.
- Gas supply flexibility contracts.
- Fines for exceeding contractual limits.
- User defined safely margins on the contractual limits
- Gas quality of entries.
- State of the network at T=0.

Main constraints are:

- Minimum and maximum pressure per node.
- Gas quality.

Objective:

- Minimize total cost.

ROUTE PLANNING

After loading network model, the route planner is asked to supply the requested exit flows within pressure and quality constraints for a minimum of total costs. The flow can be delivered via pipeline transport, line-pack, blending stations and entry points. The associated pressure gradients can be created from entry supply pressure, compressor stations and pressure reducers. The main costs factors are fuel for driving compressors, Nitrogen ballasting at blending stations and gas supply flexibility. The main challenge for the route planner is then to find a strategy for routing the gas through the network and the use of line pack for the upcoming 24 hours.

NON-LINEARITIES

The route planner would have been presented with a typical linear logistical problem, if it were not for unavoidable non-linearity's associated with gas transport. The main sources of non-linearity are:

- the non-linear relation between flow pressure drop across pipelines: $P_{in}^2 - P_{out}^2 = \lambda_* Q^2$, where P_i are the entry and exit pressures, Q the flow and λ a characteristic pipeline constant,
- dependence of compression efficiency η_{comp} (and hence fuel costs) on flow and compression ratio,
- Control of the gas quality via blending stations.

The method used to address the non-linearity was expressing the equations in terms of *variables* Q, P and *parameters* Q_{mean}, P_{mean}. In this manner the non-linear problem is translated into a linear programming (LP) problem developed around a set of Q_{mean}, P_{mean}'s and iteratered by a preprocessor in N steps until sufficient convergence is established , i.e. $Q \sim Q_{mean}$, $P \sim P_{mean}$. The typical strong points of this successive approximation approach are:

- Solving N times a LP problem still takes only little calculation time.
- Smoothed but non-linear empirical data can be included in finding cost optimal routes. Figure 2 illustrates this in case of compression efficiency of one particular station.

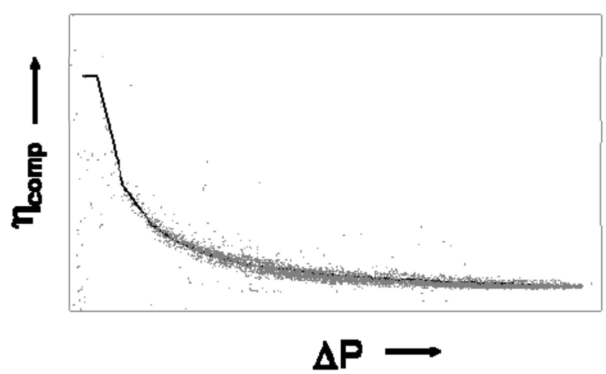

Figure 2 - measured performance data of a compressor station (points) and relation included in the route planner (solid line).

The typical weak points of the successive approximation approach are however:

- An initial state or “seed” of P_{mean}, Q_{mean} is required and the solutions may depend on the initial starting point. Moreover no guarantee can be given anymore that solutions represent true global optima.

- Networks with loops can flip-flop between solutions and fail to properly converge.

The first issue is of minor importance to a decision support tool since the application runs real time and the state of the network at T=0 and a simulator run for the upcoming 24 hours is present. Therefore no need for estimating the initial values or seed from blank. Actually the main task of the route planner will be to update the previous plan, the rolling horizon approach, or to improve upon the simulator output.

STABILIZING THE OPTIMIZER

The convergence issue is a more serious one. This because the Gasunie network contains loops of various magnitude and flip-flopping is real and constant danger. In this stage of the project it is of paramount importance that numerically accurate solutions are found on a consistent basis and the output "feels realistic". The currently implemented methods for finding accurate and realistic solutions are:

1: *increasing model "stiffness*. The preprocessor estimates the state N+1 based on state N, N-1,N-2,… This already dampens many of the fast oscillations that would occur when only state N is considered for the estimation of N+1.

2: *successive approximation in stages*. The strategy for find a solution via successive approximation is divided into distinct stages: 1) "free-for-all" : the route planner can use all stations in any desired manner to find optimal routes, 2) "filtering": compressor or blending stations that are not used or only in a marginal manners are blocked and 3) "fine tuning": the allowed bandwidth on the selected compressor or blending stations for the optimizer is decreased with each approximation.

3: *financial incentives to stimulate "smooth behavior"*: The route planner is stimulated to provide "acceptable advise" by putting penalties on undesirable behavior. This mainly refers to fines on erratic use of the compression and blending stations. In this manner the route planer is seduced to create "smooth plans" that also dampen possible pressure and quality oscillations throughout the network.

EMBEDDING IN END-USER ENVIRONMENT

The route planner was designed with a click-on approach on a simulator for optimal flexibility and minimal interference with the daily operations in mind. Figure 3 illustrates how the route planner is intended to work: the route planner receives all required information concerning network configuration, flow and gas quality forecasts, etc. from the main simulator. With this data the reduced network is calibrated and a case is constructed and presented to optimizer. The solution is then either inspected automatically or if necessary by the end-user. When a plan is accepted, it can be uploaded into the simulator for verification, closing the total loop.

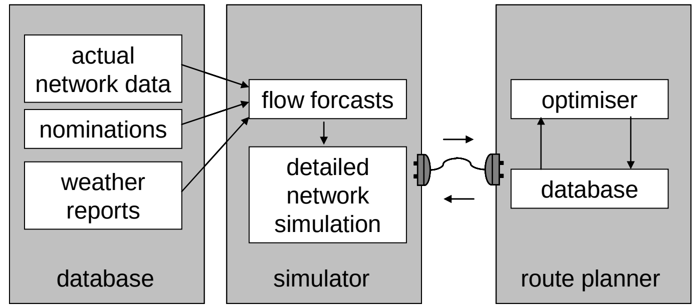

Figure 3 - a click-on approach to the route planner in to the main Gasunie database and simulator.

NETWORK CONFIGURATION

One of the main issues during the route planner development was to determine what level of detail could be handled by the route planner. Figure 4 shows the end result for a typical configuration of the Gasunie network. Eventually all essential features are present in this reduced network model. Each line in the template represents a distinct gas transport trajectory, consisting of a cluster of pipelines transporting a particular gas quality. Each network point represents either a cluster of entries or exits, gas blending, compression or pressure reducing station. A "bulls eye" around a point indicates that this station is operating near an operational pressure limit.

The challenge is to use as few points as possible to describe all the features of the network essential for station planning. Too many points will strongly decrease solving speed, too little will result in numerical inaccuracy and low quality advice. Finding the right balance is a matter of continuous fine-tuning.

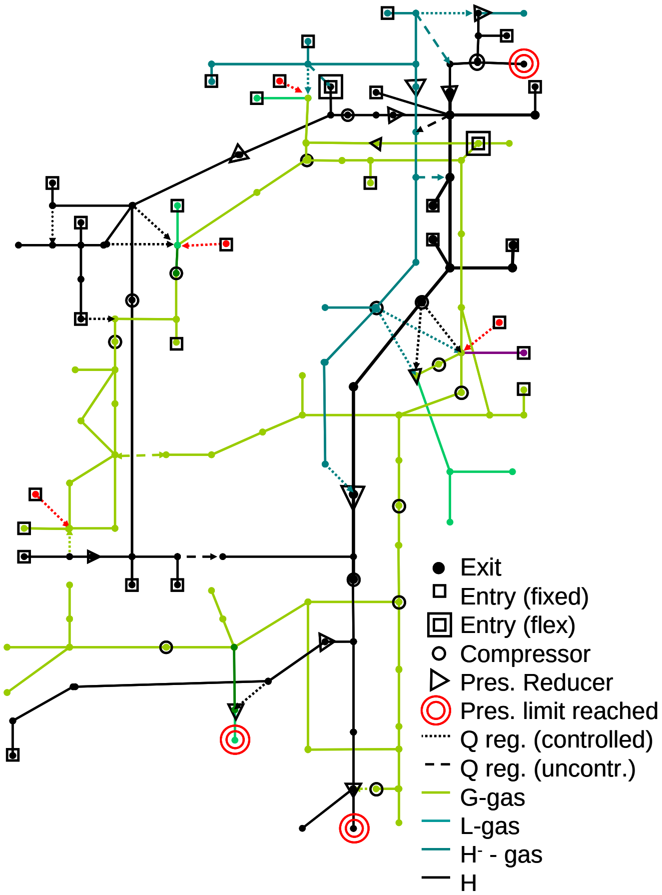

Figure 4 - route planner model in final form: the gas transport network of the Netherlands for the H^+, H^-, L and G gas quality. Points A-D refer to the graphs in figure 5.

NETWORK CALIBRATION

Once a reduced network model is created it is imperative that each trajectory and station is configured with the correct (real time) parameters. This since the allocation of pipelines per trajectory may change seasonally or temporarily due to maintenance. To enforce that the correct parameters are used a special "network calibration routine" is devised for the route planner:

1) each point of a trajectory is associated with a physical location in the complete simulator network. These points provide the real time P_{in} and P_{out} references for the reduced route planner network.

2) an output of a simulator is then analyzed to determine the effective relation between P_{in} and P_{out} the associated real time flow Q_{eff} through the real network. This data is then used to reconstruct $\lambda_{eff,i}$ (as in $P_{in,i}^2 - P_{out,i}^2 = \lambda_{eff,i*} Q_{eff,i}$) for trajectory i during the calibration interval.

3) a report is generated displaying the newly found λ's, the accuracy of the values during the calibration period and alarms on large discrepancies with the last known good values.

This calibration procedure clearly illustrates the special relation of the route planner with the main simulator and the clear division of tasks. The task of the simulator is to generate flow predictions and a "common sense" gas transport strategy for the upcoming day. The route planner analyses the output and tries by all allowable means to improve upon the "common sense" strategy.

RESULTS

In 2009 the first experiences were obtained with the full route planner prototype for typical summer, spring, autumn and winter conditions. In offline and/or near real time tests various days were replayed and the difference between the route planner and the actual dispatcher strategies were analyzed.

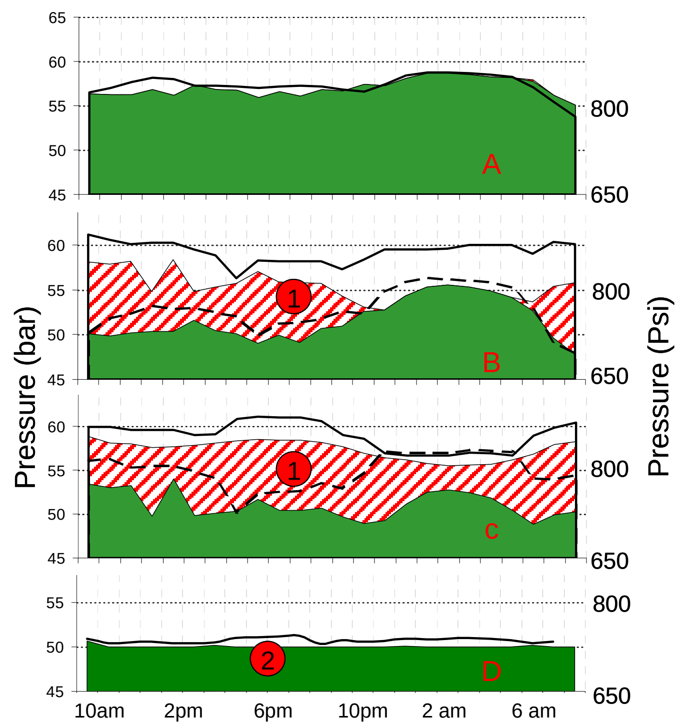

Figure 5: Pressures on the "north-south G-gas line" during a typical winter day (10 AM to 10 AM). See figure 4 for the location of compressor stations A-C and export station D. The solid surfaces indicates the incoming pressure levels and the dashed surfaces the outgoing pressures as proposed by the route planner. The dashed line indicates the actual incoming pressure, the solid line the outgoing pressures. See text for explanation of bullet 1 and 2.

EXAMPLE OUTPUT

Figure 5 illustrates the process in the form of the graphs showing the predicted/proposed pressures by the route planner and the actual values along the "North-south G-gas line" (see A-D in figure 5), of the network during a typical winter day. Figure 5 illustrates that the begin and end pressures are usually highly similar, but in between other choices may have been made by the route planner, in particular:

1. The route planner may have used the compressor stations in a different preferential orders and magnitude.

2. The route planner here has the advantage of hindsight and will usually exactly meet the minimum exit pressures (contractual +margins).

3. The route planner will often use blending stations in (slightly) different manners.

4. The route planner may use the flexibility of the entries and the buffer of the network in different manner.

5. The route planner may use pressure reducers in a different manners in order to build up and release the line-pack in sections of the network.

In figure 5, bullet 1 highlights that in this example the route planner used station B and C in a complementary manner with respect to the dispatchers. Bullet 2 highlights that the route planner indeed ensures that the exact required pressure (contractual+ safety margin) was met at the exit station. The other factors are also present in this example, resulting in small differences in predicted and actual pressures. However disentangling these factors is usually not straightforward.

KEY INSIGHTS

The key result of the offline tests was that the route planner can make "intelligent strategies" and, due to the stabilization methods described in the previous chapter, with a "realistic feel" to them. The results of figure 5 were only obtained after the model was adapted to handle the following issues:

- The main focus during the design period of the route planner was on accurate modeling of compression. During the test it however became clear that the real challenge is in the modeling of the blending stations including nitrogen ballasting. This in particular since the network contains blending stations where the mixing flow can range up to 100% of the output flow. Especially during the low-flow summer situations this can create "flip-flop interaction" between blending stations (see section "stabilizing the optimizer").

- The route planner will "exploit" each inaccuracy in the reduced network configuration to achieve cost savings that are not real. This puts a much greater emphasis on numerical accuracy then first expected and requiring the development (see section "network calibration").

- In nearly all cases the route planner managed to save between 0 and 20% in total costs. The optimizer engine does however not explain how a certain saving was obtained and where it apparently "outsmarted" the dispatcher. This puts a great emphasis on organizing the GUI in such a manner that the end-user can find any information quickly. For instance, merely being able to monitoring the evolution of the plans during the solving phase provides crucial insights which part of the network holds the "key" to the optimal strategy.

- The consensus during the off-line tests was that the primary aim of the route planner decision support tool is to prove itself as a "strategic advisor" to the dispatchers and to the main simulator, not on calculating detailed set points. This reinforced the idea that the route planner should form a team with the simulator, rather then replacing it.

SPIN OFF: COST TRANSPARENCY

One of the new insights gained during the testing of the prototype was that the route planner may have other modes of use that could potentially be of equal business value. The route planner aims to take all factors into account that influence the decision making of the dispatchers. These include a near complete list of the conscious and "subconscious" operational margins the dispatchers will use to ensure security of supply during demands surges, supply interruptions, shipper renominations and station failure. Each operational margin will have an impact on the overall costs of gas transport and can itself potentially be optimized. This is illustrated conceptually in Figure 6. For the route planner system it is rather straight forward to re-run cases with various flow scenarios and levels of margins and thus quantize the cost impact for each operational margin. However, exactly how this secondary application could function in practice will be explored after the primary function i.e. decision support tool, has been established.

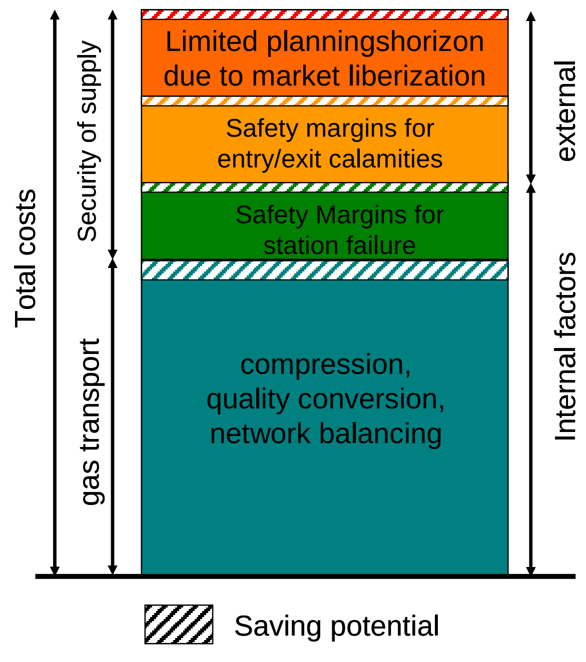

Figure 6: breakdown of the total cost of daily gas transport process. The dashed areas indicate that each intentional or unintentional operational margin for the route planner to quantize or even optimize.

SUMMARY

The prototype has demonstrated to be able to maintain the "apparent intelligence" even for a five times more complex network as used for the proof of concept, creating plans with a similar feel to them as those made by dispatchers. The replay of real summer and winter days demonstrated that:

- dedicated routines for the automatic calibration of the reduced network models are essential for gaining trust in the tool and lending credibility in the predicted saving.
- Modelling the blending stations and nitrogen ballasting during the low flow summer situations proved to be even more challenging to the optimiser engine then the modelling of the compressor stations during the winter. To this end special "stabilization tricks" were developed for the optimizer engine.
- The tests demonstrated that the main task of the route planner is to provide strategic advice on the use of stations, rather then providing detailed set points for a particular station. This illustrates once more that the route planner is intended to work together with a simulator, rather then replacing it.
- In principle it is rather straight forward for the route planner to rerun past and future cases with various levels of safety margins, thus providing insight in the cost impact of these deliberate and more subconscious choices.

FUTURE WORK

The current focus is on finalizing the work on the prototype system, preparing and testing it for continuous operation in the control room. Once sufficient experience is gained with the decision support tool and numerical accuracy is deemed high enough, potentially equally valuable spin-off applications will be examined in more detail.

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ACKNOWLEDGEMENT

We would like to thank Gas Transport Services for making the project possible and for the many technical and conceptual discussions on the best way forward.

Author biographies

Dr. Jan Willem Turkstra is a researcher and project manager at the former Gasunie Engineering & Technology (GET), now part of KEMA. He received his PhD. degree in 2001 for his work on interactions of highly charged ions with laser cooled Sodium atoms. At GET he developed a simulation environment for the analysis and optimization of complex domestic heating and cooling appliances such as solar combination boilers and micro-CHP. Currently he is involved in the development innovative methods for the optimization of the Dutch gas transport system.

Dr. Robert van der Geest is Senior Consultant Gas Transport in the new business unit Gas Consulting & Services that KEMA acquired in July 2009 by taking over the R&D activities of Gasunie, the Dutch gas transmission system operator. Within Gasunie, he worked as R&D manager in the area of operations research. Together with his team he has carried out a number of projects in the area of asset management and operations of gas transport, such as benchmarking of the Dutch gas transport system, development of an optimization tool for operational gas transport, development of a new method for long-term investment planning in gas transport capacity, development of a new method for planning of inspections and maintenance of high-pressure pipelines, and the technical assessment of a number of gas transport companies in North-West Europe for potential acquisition. Prior to joining Gasunie, Dr. van der Geest worked on the development of advanced tools for offshore oil and gas production processes with Asea Brown Boveri (ABB) in Norway. He holds a Master's degree in Economics and a Master's degree in Computer Science from the University of Groningen, and a Doctorate in Mathematics from the University of Twente in the Netherlands.

FIGURES

Figure 2 - example of the network blocks used in the route planner (blending station).

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