Semi-optimised pipeline routing for CO₂ Capture and Storage

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Abstract

PSS Router is an integrated routing application within the PSS II Simulator. This techno-economic simulator has been developed specifically to address questions relating to the deployment of CO₂ capture and storage in Belgium.

A spread algorithm is used for least-cost raster routing instead of the more commonly used Dijkstra algorithm, which is generally slower for raster routing because of its calculation-intense route sorting. Instead of the traditional 8 directions, 32 directions (up to three raster points further) can be chosen from a certain raster point with PSS Router to create smoother and more realistic routes. A matrix of cost factors is built to calculate pipeline investment costs using material, labour, right of way and miscellaneous (engineering etc.) costs. Vector data is added to simulate objects such as roads and rivers. This combination of raster and vector cost data allows fast, realistic and detailed routing and cost calibration.

PSS Router has the ability of creating pipeline networks in two different ways. A first method is creating networks within one time step. Thus, not only an extra CO₂-source can be connected to an existing pipeline, but one new source is able to connect to multiple CO₂-sinks and vice versa. In PSS Router this is limited to two sources and one sink. Higher configurations would demand an unrealistic calculation time. The second method does not suffer from these limitations. It simulates the building of a network over different time steps using backward discounting, which results in enlarging existing pipelines for joint use. This method introduces the concept of limited foresight for simulating realistic, semi-optimised pipeline networks.

Keywords: CO₂ Capture and Storage, techno-economic simulation, pipeline routing, networks

1. Introduction

CCS (CO₂ Capture and geological Storage) will most likely become an important tool for climate mitigation. CO₂ will be captured at industrial installations (sources) and injected into deep geological formations (sinks) for safe and permanent storage. CCS is currently applied in several commercial and demonstration projects, and different capture techniques are under development. In most cases CO₂ producing industry is not located right above a suitable storage reservoir. Thus a need for CO₂ transport is created, sometimes for up to hundreds of kilometres. While CO₂ transport via ship is
possible, carbon steel pipelines will most likely become the main CO\textsubscript{2} transport method.

The PSS II simulator was developed within the PSS-CCS projects (Piessens et al., 2009) to make projections on the deployment of CCS in Belgium. The PSS II simulator is a techno-economic simulator for the deployment of CCS. Because of the nature of the technology, it has a focus on geological and technological uncertainties. In order to simulate realistic integrated CCS projects, a least-cost routing algorithm is needed for pipeline simulation. An innovative approach is used in the PSS II simulator to handle the special situation of CCS technology which resulted in a module called PSS Router.

PSS Router is an integrated routing application within the PSS II simulator. This techno-economic simulator has been developed specifically to address questions relating to the deployment of CO\textsubscript{2} capture and storage in Belgium. The PSS II simulator uses repeated calculations with stochastic parameters (Monte-Carlo method) for handling uncertainties. Each part of the simulator, including PSS Router, will run multiple times and calculations should therefore be made as fast as possible. Material cost, labour, right of way and miscellaneous (engineering etc.) costs, each depending on the type of terrain crossed, have to be included, as well as linear obstacles such as railways, roads and rivers.

It is likely that once CCS technology becomes widely available, a CO\textsubscript{2} pipeline network will emerge. This network will connect several CO\textsubscript{2} sources to several CO\textsubscript{2} storage sites. A CCS infrastructure simulator should be able to simulate this kind of networks in a realistic way. The PSS II simulation process is therefore based on the simulation of project decisions, which are made using real options analysis in combination with the portfolio theory. Pipelines trajectories should also follow least-cost routes and form least-cost networks. Two networking methods will be presented here that are implemented in PSS II.

2. State-of-the-art

Several routing algorithms are developed specially for CCS applications. Most of these (e.g. Odenberger et al., 2008) use a single-source – single-sink configuration, or a limited number of sources and sinks.

The simCCS model (Middleton & Bielicki, 2009; Keating et al., in press; Kuby et al., in press; Middleton et al., in press) is a CCS infrastructure simulation model that includes pipeline routing. It calculates several possible pipeline routes. Then a manual generalisation step follows, resulting in a network of a limited number of possible paths for pipelines that are likely the best routes. The model will then simulate pipelines along a selection of these predetermined paths. This method does not create the optimal pipeline routes or network, because of the generalisation step. This step was probably introduced to keep calculation time within realistic limits.

Morbee et al. (in press) have developed the InfraCCS tool to simulate CCS infrastructure, building on the methodology of Middleton & Bielicki (2009), and was applied to the European context. With InfraCCS, transport between European countries is simulated, using the principle of perfect foresight.
3. Pipeline routing

A PSS II simulated pipeline consists of an initial compressor to bring the CO\textsubscript{2} at the appropriate pressure for transport, a pipeline and a number of booster stations along the way to maintain pressure.

Figure 1: The standard 8-directions raster routing. This method will create very jaggy route paths.

Figure 2: Advanced 32-directions raster routing. Route segments can go up to three cells further, with on average a 11.25 degree interval, creating much more smoothed routing paths.

The total transport cost is calculated summing the discounted pipeline investment cost (INV\textsubscript{p}), the discounted compression investment cost, the compression fixed operation and maintenance cost, and the compression variable operation and maintenance cost. The INV\textsubscript{p} on its turn consists of the material cost, labour cost, right of way and damages, and miscellaneous costs (engineering etc.). These cost factors will be multiplied by a terrain factor that depends on soil type, land use, topography and regional differences. The cost factors of these four data types each correspond to a raster grid. An additional cost factor is added for crossing certain linear, localized objects, such as rivers, roads and railways, which are represented as vectors. This cost factor is applied to the INV\textsubscript{p} and depends on the type and number of objects to be crossed and the width of the crossings. This way raster data (cost grids) and vector data define the total cost of the pipeline, which needs to be minimised in order to find the least-cost pipeline trajectory.
The commonly used Dijkstra algorithm (Dijkstra, 1959) or derivates are excellent shortest-route or least-cost routing algorithms that are generally used in e.g. GPS routing on vectorised maps of streets and their crossings. Their performance is limited by the calculation-intense route sorting step that is intrinsic to this type of algorithms. A spread algorithm is used in PSS Router instead, which is faster because it avoids sorting by using the known distances between the cost grid cells off raster data as an approximately sorted tree which in general can be converted with few iterations into one of true least-cost routes.

On a standard routing raster, 8 directions can be chosen from one node to the next. This means a route segment can have a 45 degree interval direction (figure 1). This method will create jaggy route paths. When route segment are allowed to jump up to three raster points, 32 directions are possible, with an average 11.25 degree interval (figure 2). This creates more smoothed and realistic route paths, and usually also increases the overall performance of the routing application because the pipeline is found in fewer steps (corresponding to the number of pipeline segments).

4. Pipeline networks

PSS Router has the ability of creating pipeline networks in two different ways.

A first method is creating networks within one time step. PSS Router calculates the trajectory from one node to all other nodes (but visualises only the optimal route between two points). Consider a simplified network of two CO₂ sources and one CO₂ storage site (figure 3). If the routing algorithm is applied three times, with both CO₂ sources and the CO₂ storage site as starting points, then it is a matter of summing up the three transport costs in each potential node (each raster cell). The node with the minimal cost is the optimal branching point for this network. This method can be expanded by consecutive calculations for additional CO₂ sources and storage sites. In a single time step, an entire CCS network can be built this way. This multiple-source – multiple-sink pipeline transport network is the least-cost solution for this configuration in this time step, and is therefore a truly optimized solution (figure 4).

Figure 3: Two sources and one sink are connected through a pipeline branching point. Calculating three least-cost routes from the sources and sink, the optimal branching point can be found.

Figure 4: An optimised multiple-source – multiple-sink network. This is the least-cost network for this set of projects.
A second method simulates the building of a network over different time steps. If in a certain time step a pipeline is simulated, in a later time step another new CCS project may want to use that same trajectory. The pipeline will then be enlarged for the additional capacity (figure 5). It would not be realistic to just discount the additional costs over the second, new project’s lifetime since the pipeline would in reality have the enlarged size from the start of the first project. These additional investment costs are therefore discounted backwards for the time between the start of the first and second project, and added to the second (new) project’s costs. This method allows creating a network over different time steps, which is however not a truly optimised network (i.e. the cheapest option for a certain configuration at a certain moment). It also presumes a pipeline can operate at any smaller capacity than its native. In reality there are pressure constraints limiting the capacity range of a pipeline.

Figure 5: An existing single-source – single-sink pipeline (a). It might be profitable to re-use (part of) the same pipeline trajectory for another project (b). Initially, a higher-capacity pipeline should have been built (c). The extra cost for this pipeline enlargement will be backward discounted and added to the new project.

Investment costs in PSS II are generally discounted over the whole CCS project’s lifetime. In a normal discounting situation for a single pipeline, the yearly investment cost is calculated as follows:

\[ INV_y = INV_t \times FCF \]
with

\[ INV_y = \text{Yearly discounted investment cost} \]

\[ INV_t = \text{Total investment cost} \]

\[ FCF = \text{Fixed charge factor for discounting} \]

and

\[ FCF = \frac{\text{DiscRate}}{1 - (1 + \text{DiscRate})^{-\text{DiscTime}}} \]

with

\[ FCF = \text{Fixed charge factor for discounting} \]

\[ \text{DiscRate} = \text{Yearly discount rate} \]

\[ \text{DiscTime} = \text{Discounting time (generally project's lifetime)} \]

Imagine pipeline 1 existing and a new pipeline 2 using part of pipeline 1, as in figure 5c. In standard calculations, the principle of discounting reduces the costs of future expenditures. Similarly, backwards discounting will make past investments more expensive. The backwards discounted investment cost for the shared segment of pipeline 2 will be (only for the period between the start of project 1 and 2):

\[ INV_{ye2} = \frac{INV_{t2} - INV_{t1}}{DiscRate_1^{-\text{DiscTime}_{diff}}} \]

with

\[ INV_{ye2} = \text{Extra yearly backward discounted investment cost for the shared segment} \]

\[ INV_{t2} = \text{New total investment cost for the shared segment (capacity of both projects)} \]

\[ INV_{t1} = \text{Old total investment cost for the shared segment (capacity of project 1)} \]

\[ DiscRate_1 = \text{Discount rate of project 1} \]

\[ DiscTime_{diff} = \text{Discount time in the past (start year project 1 − start year project 2)} \]

To calculate the whole investment cost of the new pipeline, the investment cost for ‘now’ until the project’s end will be added later using the first formula. Also, a connection cost will be added to the investment cost for each branching point.

5. Use and limitations
The first method, for calculating optimised networks, gives the option to make perfect forecasts on pipeline networks. However, a typical calculation in PSS Router at national scale for a single pipeline takes about one second on a modern computer (about half an hour for the total PSS Router calculation for Belgium), while the dual-source – single-sink configuration takes about 46 times longer. Expanding this to a multiple-source – single-sink, or a multiple-source – multiple-sink configuration would increase calculation time with a factor 300 to about 10000 respectively, depending on the number of sources and sinks. Considering a calculation time of about thirty minutes for the single pipeline method, and the fact that PSS II is based on repeated calculations, a simulation time of at least 200 days is achieved. This is from a practical point of view not an option. The dual-source – single-sink configuration is implemented in the PSS II simulator but is, because of the practical constraints, only used for academic issues, such as estimating the cost differences between truly and semi-optimised pipeline networks.

It can also be argued that simulations based on a truly optimised network will lead to underestimated infrastructural costs, because in real life the optimal solution can rarely be achieved. An entire network is built over different time steps depending changing needs, and is therefore by definition not truly optimal.

Limited foresight simulations can therefore be expected to produce the most realistic results. Such results are provided by the second method, because it allows to retroactively upgrade sections of existing pipelines to future needs (limited-foresight because the paths are already fixed, but the capacity can be optimized).

6. Results

The PSS II simulator is at the time of writing in its very last stages of testing and has produced some preliminary results with semi-optimised pipeline networking enabled. In this test scenario two locations are defined for building new sources, and about a dozen sink injection locations are available.

Figure 6: A pipeline network calculated by the PSS II simulator for one Monte-Carlo calculation from 2010 until 2050. The yellow circles are source locations, green triangles sink injection points and red dots pipeline connections. Pipelines from different time steps are in different colours. PSS Router is capable of calculating realistic pipeline routes and networks, pipeline capacities are given in the legend in Mt/y. Coordinate numbers are in Belgian Lambert (meter scale).
One Monte-Carlo calculation round (one calculation with yearly time steps from 2010 until 2050) is presented here as preliminary result (figure 6). The routes therefore have no practical value; they only serve to illustrate the functions and possibilities of PSS Router. PSS Router currently uses a cost grid with a 5 km resolution for Belgium. Optimal pipeline routing in one time step is disabled; the second networking method is enabled. In two locations sources can be built (yellow circles); multiple sources on the same location are possible. Several CCS projects are activated in different time steps, resulting in the differently coloured pipeline trajectories. The green triangles represent the sink injection locations. Pipeline branching points are indicated with a red dot.

These preliminary results indicate that the routing method works and produces realistic results. Pipeline networks are being built by the PSS II simulator. As can be observed, the shortest route is seldom the cheapest and the 32-direction method is able to create relatively smooth pipeline trajectories. Using the final input data, PSS Router, and the PSS II simulator as a whole, will be valorised in the coming months.

7. Conclusion

The PSS Router algorithm seems to produce realistic and smoothed pipeline routes. The semi-optimal routing method using backward discounting and network building over different time steps is the best option for the PSS II simulator. Next to the ability of handling all necessary raster and vector data, it maintains two important requirements: fast calculation speed and limited foresight. The single time step networking method will only be used in a dual-source – single-sink configuration due to the excessive calculation time and even then only to address specific issues.

References


